The Accelerating Universe & Dark Energy

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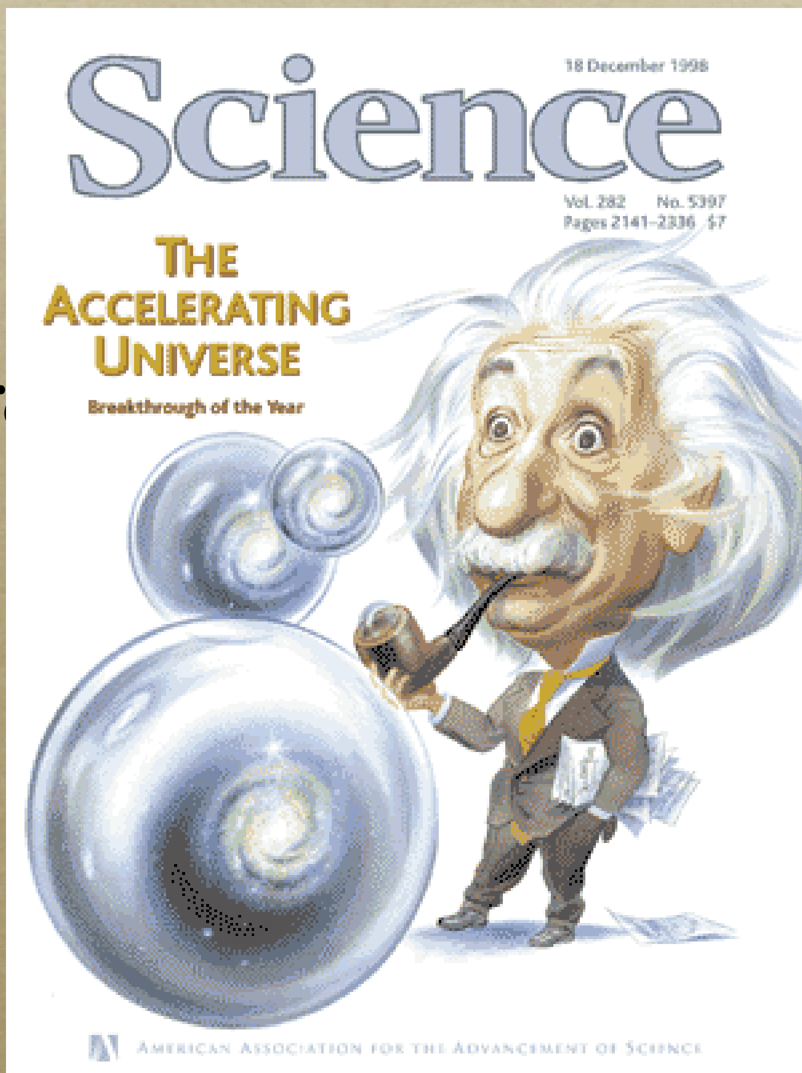
Interesting Physics



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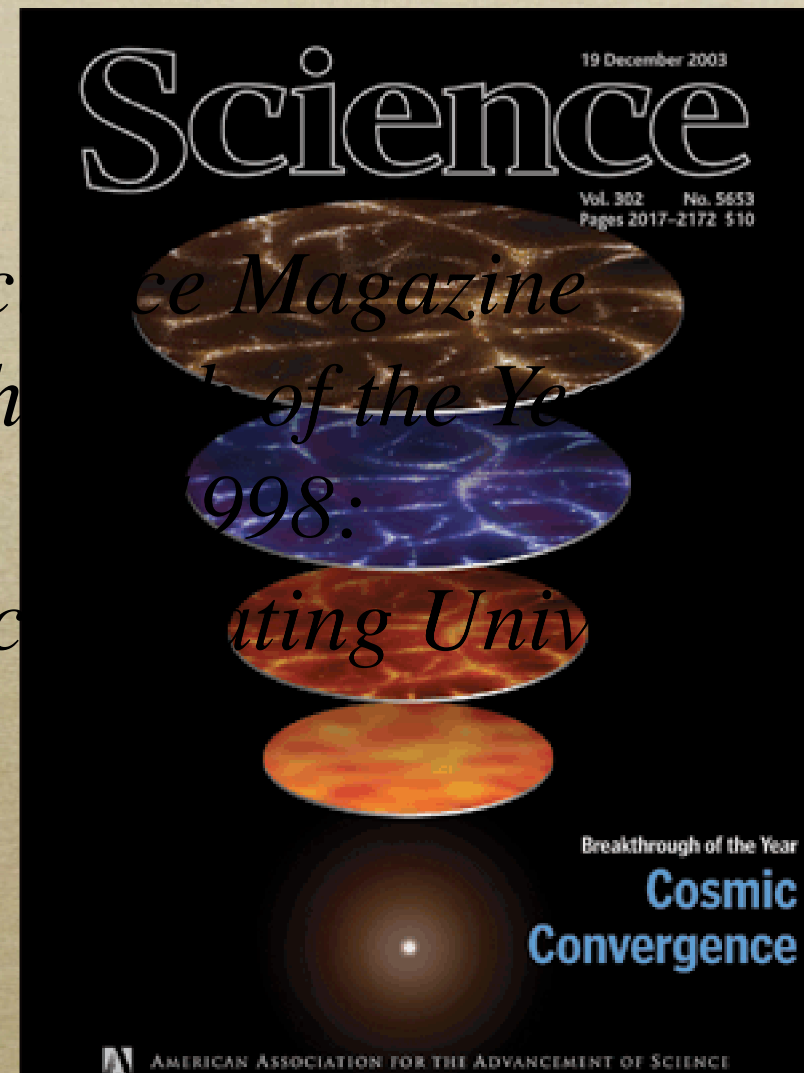


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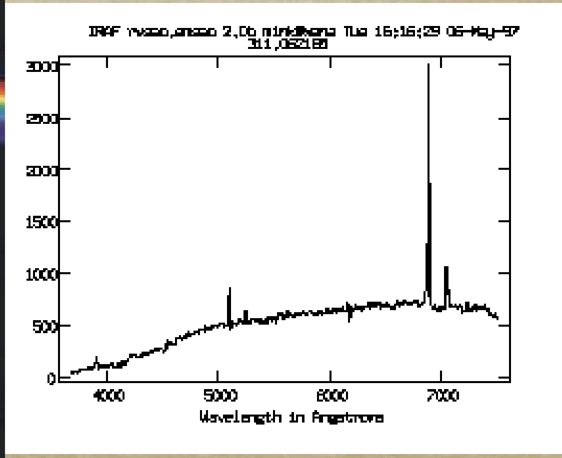
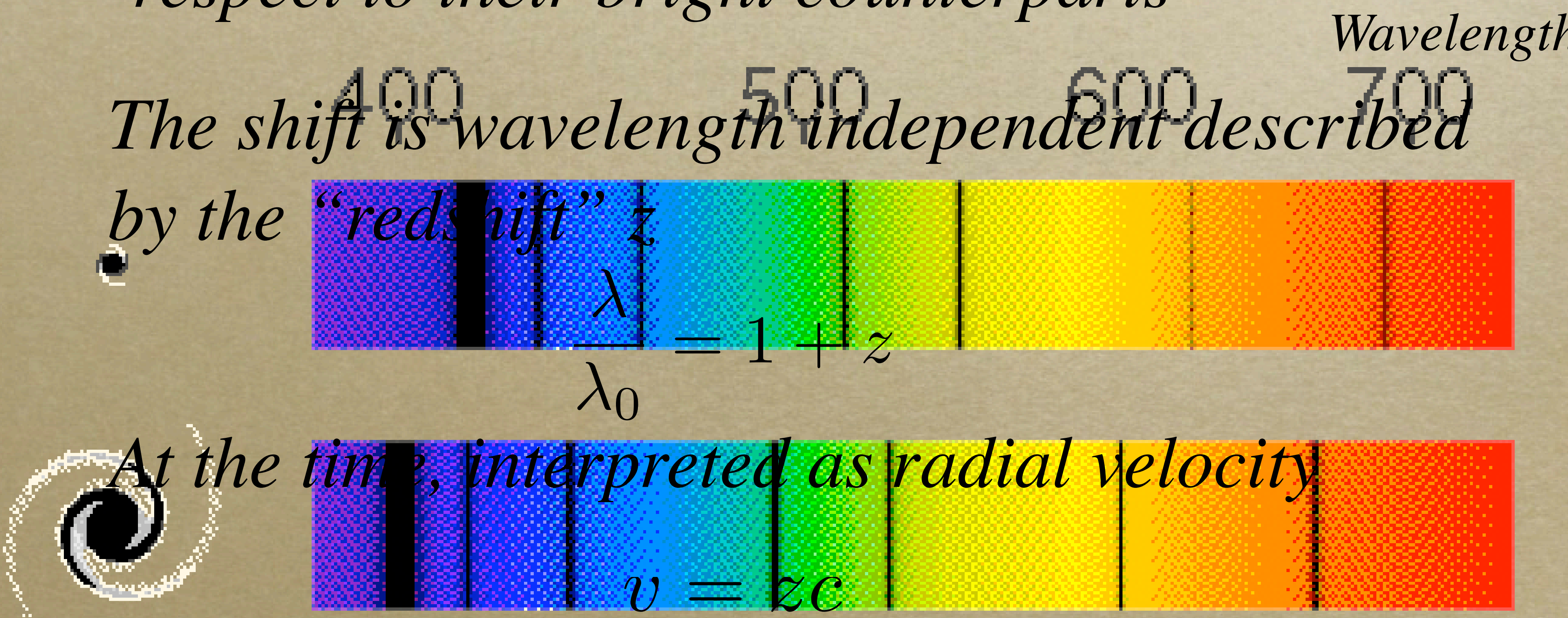
Spectroscopy



Redshift

- *Faint nebulae (galaxies) were observed to have the same spectral lines shifted with respect to their bright counterparts*



The shift is wavelength independent described by the "redshift" z

$$\frac{\lambda}{\lambda_0} = 1 + z$$

At the time, interpreted as radial velocity

$$v = zc$$

Hubble Law

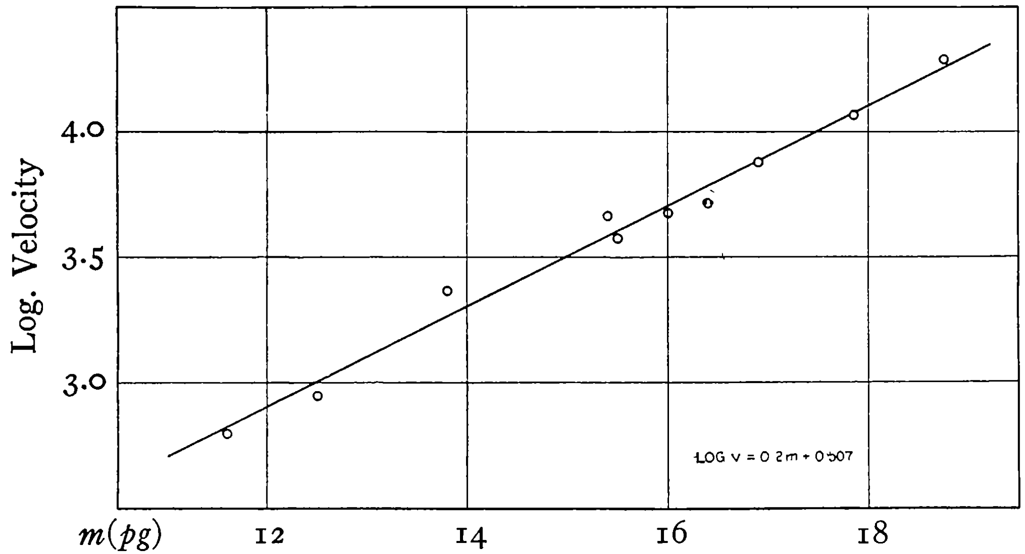


FIG. 4.—Correlation between the quantities actually observed in deriving the velocity-distance relation. Each point represents the mean of the logarithms of the observed red-shifts (expressed on a scale of velocities) for a cluster or group of nebulae, as a function of the mean or most frequent apparent photographic magnitude.

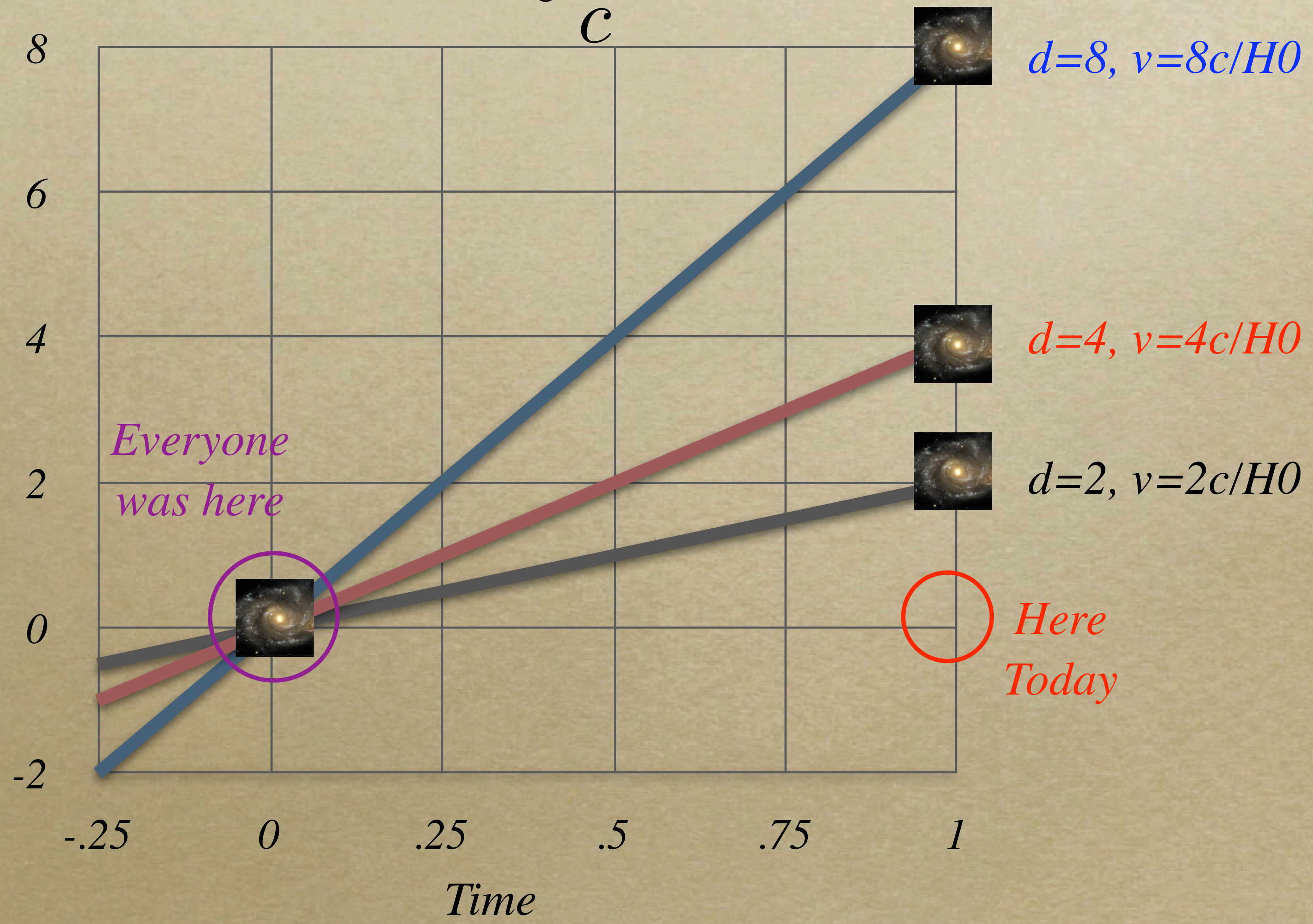
A linear relationship between galaxy redshift (velocity) and brightness (distance)

$$d = H_0 \frac{v}{c}$$

Hubble & Humason (1931)

Feature of the Hubble Law

$$d = H_0 \frac{v}{c}$$

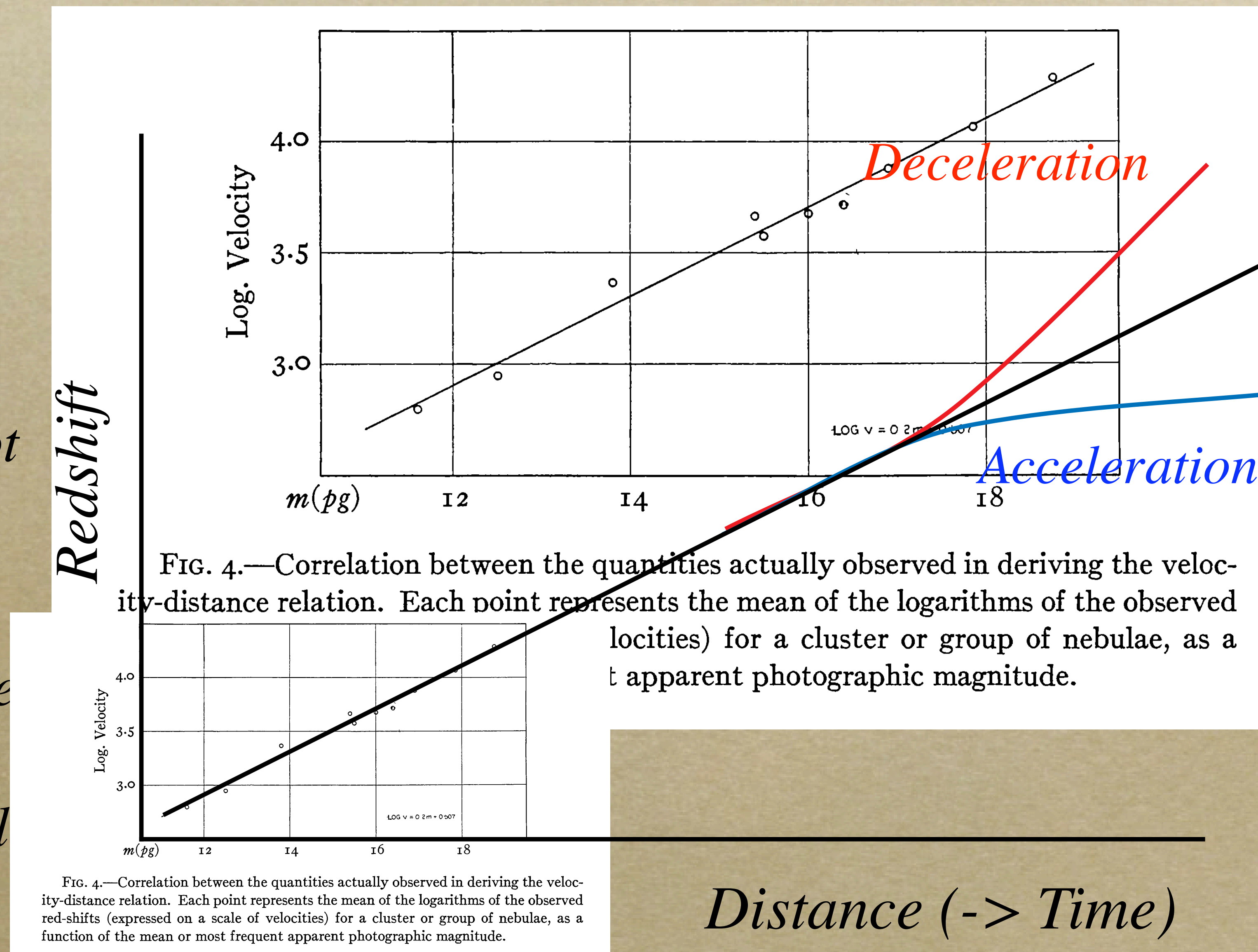


The Age of the Universe?

- *When was the Big Bang if we use this linear extrapolation?*
- *H0=558* ± 10% *km/s/Mpc (Hubble & Humason 1931)*
    - *Age of the Universe is 1.75 Gyr*
- *H0=71* ± 3 *km/s/Mpc (Eidelman et al. 2004)*
- *Systematic errors are important!*

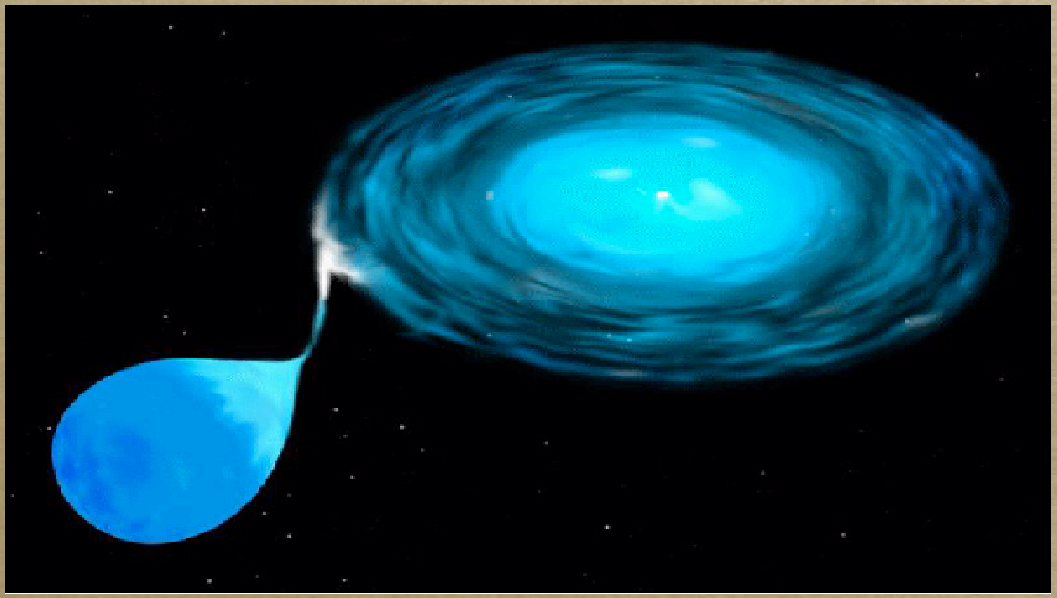
Gravity and Acceleration

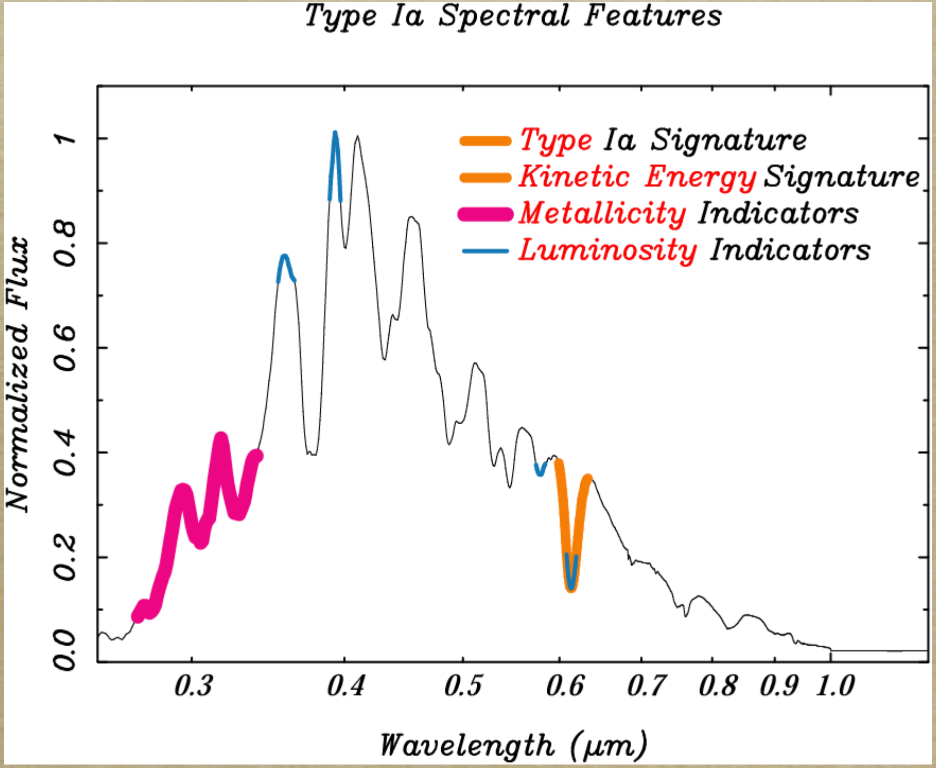
- *The force of gravity should provide some kind of acceleration, not a constant velocity*
- *Seen through the deviation from the linear Hubbl law*



Standard Candle: Type Ia Supernovae

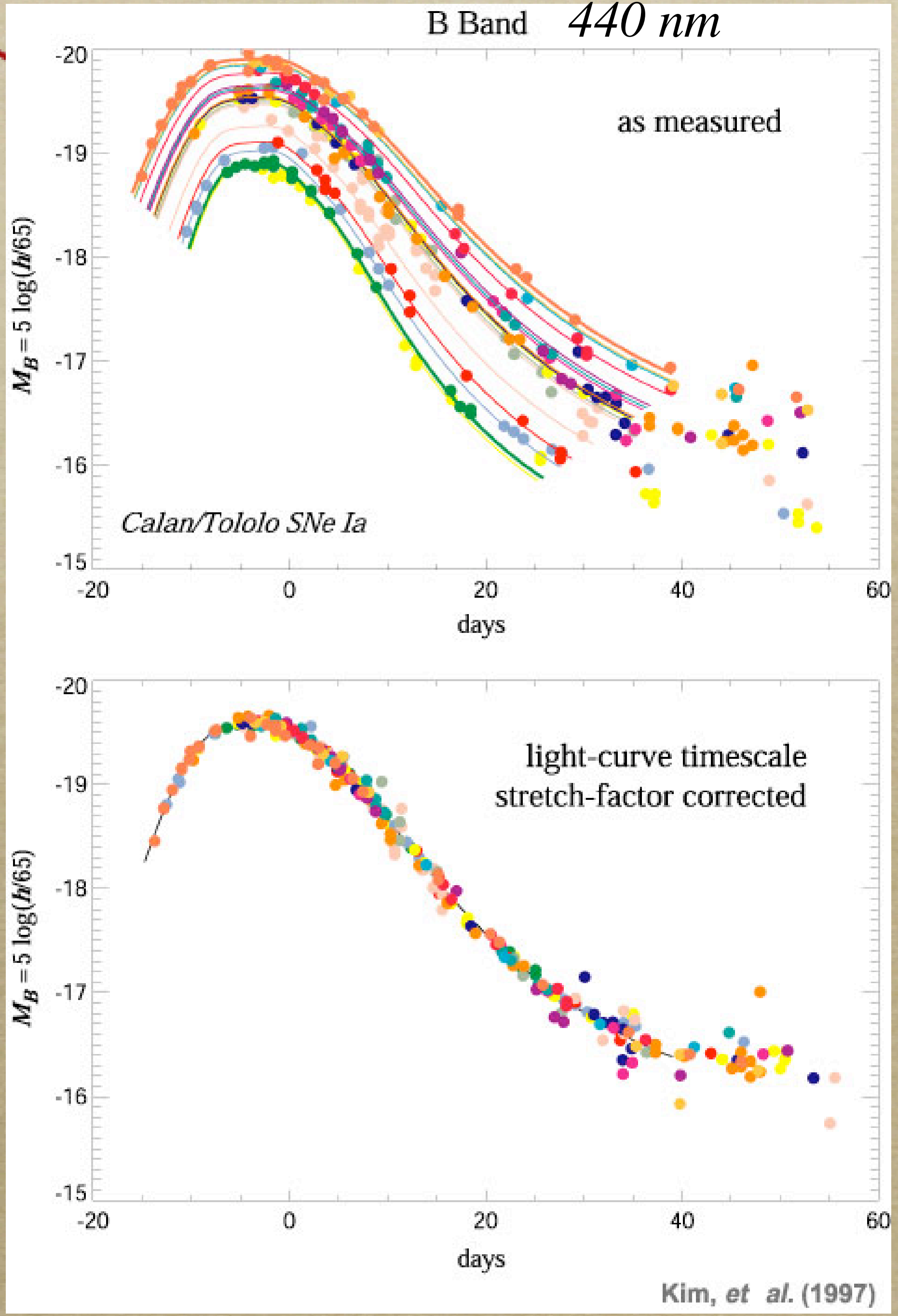
- *Defined empirically as supernovae without Hydrogen but with Silicon*
- *Progenitor understood as a C/O White Dwarf accreting material from a binary companion*
- *As the White Dwarf reaches Chandrasekhar mass, a thermonuclear runaway is triggered*
- *A natural triggered and standard bomb*



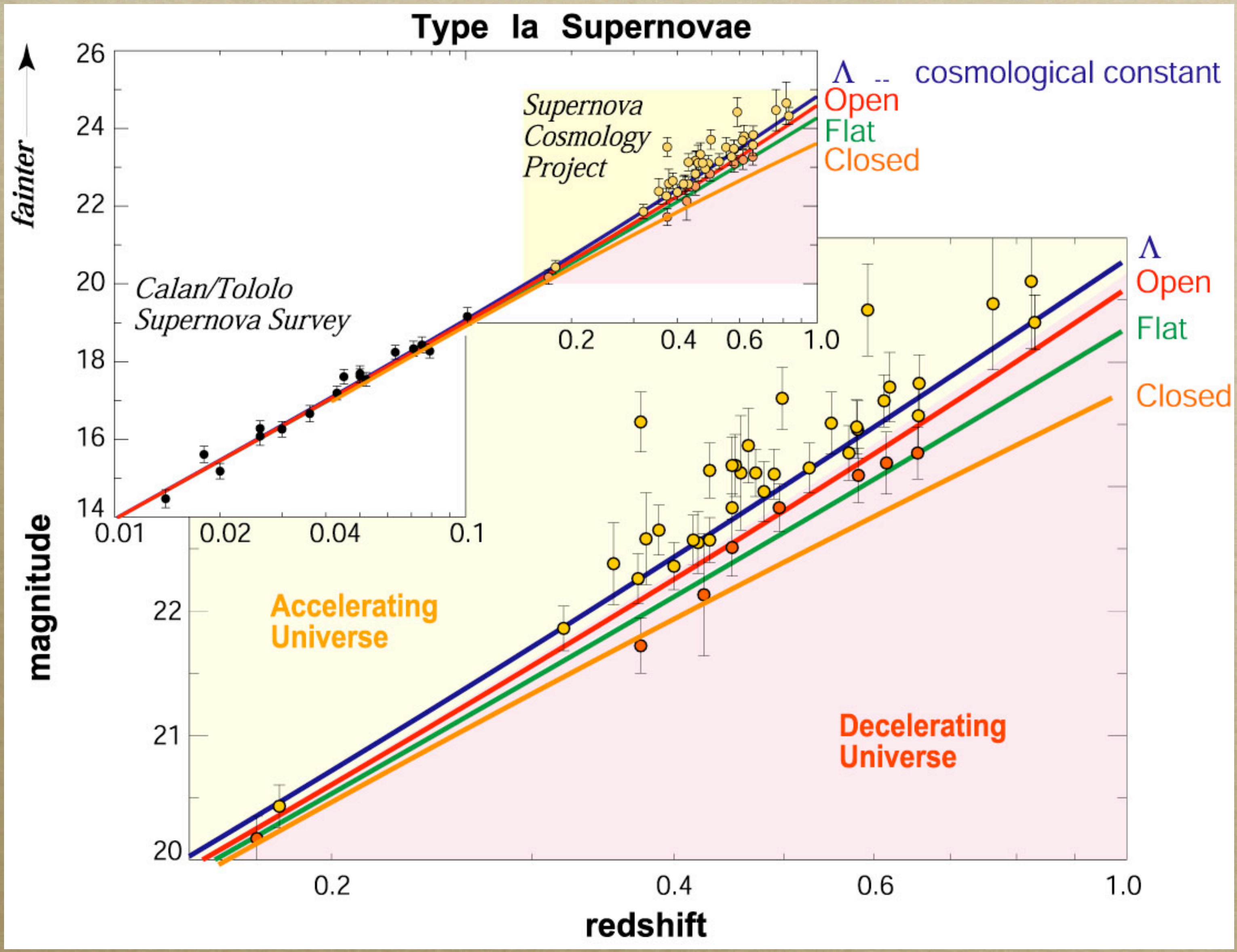


Type Ia Supernovae as Standard Candles

- *After correction for foreground dust, supernovae have peak-magnitude dispersion of 0.25 - 0.3 magnitudes*
- *After correction for light-curve shape supernovae become "calibrated" candles with ~0.15 magnitude dispersion*



Supernova Results



Look for new results soon from SNLS!

Cosmology Theory

- *Kinematics to Dynamics*
- *Cosmological principle: a homogeneous and isotropic Universe can be described by a single function, the scale factor a(t)*
- *Robertson-Walker metric*

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

- *k = -1, 0, 1 for open, flat, or closed geometries*

Friedmann Equations

- *Combine R-W metric and General Relativity to give the equations of motion for a(t)*

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$ *"Newton's Law of Gravitation"*

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho - ka^{-2}$$ *"Conservation of Energy"*

ρ - *Energy density of the Universe's constituents*

p - Pressure of the Universe's constituents

$$p < -\frac{\rho}{3} \rightarrow \frac{\ddot{a}}{a} > 0$$ *Acceleration*

Normal vs Strange

- *Solve Friedmann Equations depending on what the Universe is made of (k=0)*

Non-relativistic matter: $\rho \propto a^{-3}; p = 0 \rightarrow a(t) \propto t^{2/3}$ $\quad \ddot{a} < 0$

Radiation: $\rho \propto a^{-4}; p = \frac{\rho}{3} \rightarrow a(t) \propto t^{1/2}$ $\quad \ddot{a} < 0$

Dark Energy: $\rho \propto a^{-3(1+w)}; p = w\rho \rightarrow a(t) \propto t^{\frac{2}{3(1+w)}}$

$$\ddot{a} > 0 \text{ if } w < -\frac{1}{3}$$

Cosmological Constant w=-1 : $\rho \propto a^{0}; p = -\rho \rightarrow a(t) \propto e^{Ht}$ $\quad \ddot{a} > 0$

Fit data with the free parameters: ρ_x*, k, and w*

Common Notation

- *Parameterize w*
  - $w(a) = w = constant$
  - $w(a) = w_0 + w_a(1-a)$
- $\Omega_X = \dfrac{8\pi G \rho_X}{3H_0^2}$ *dimensionless energy density*

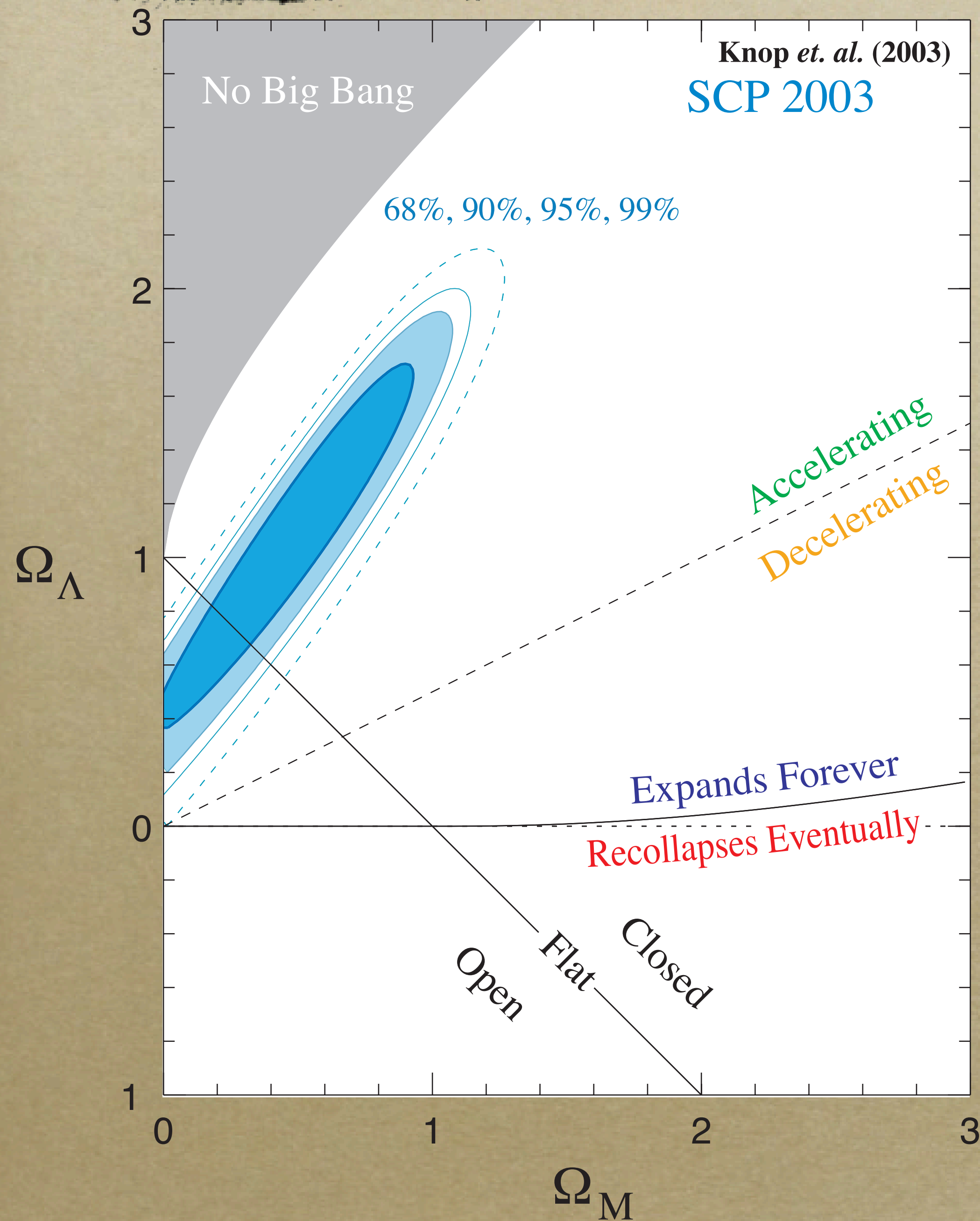
Connection to Hubble Diagram

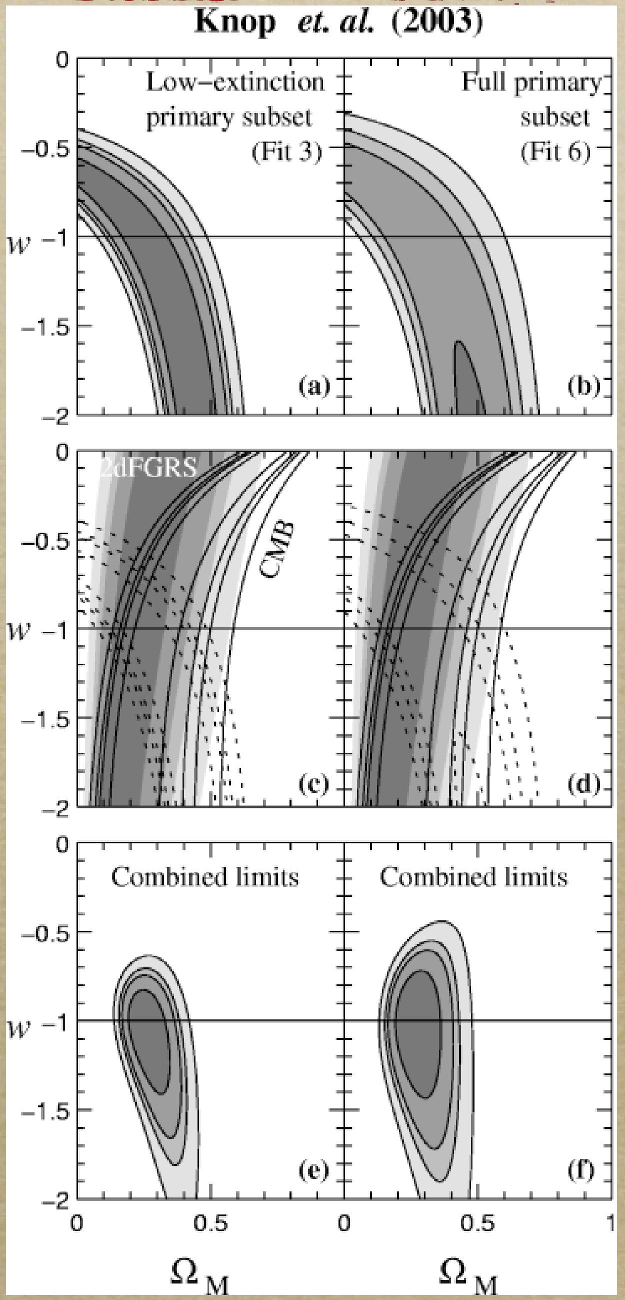
- *Redshift due to adiabatic expansion of the Universe* $$\frac{a_0}{a} = (1+z)$$
- *Brightness*

$$f = \frac{L}{4\pi(1+z)^2 d(z)^2}$$

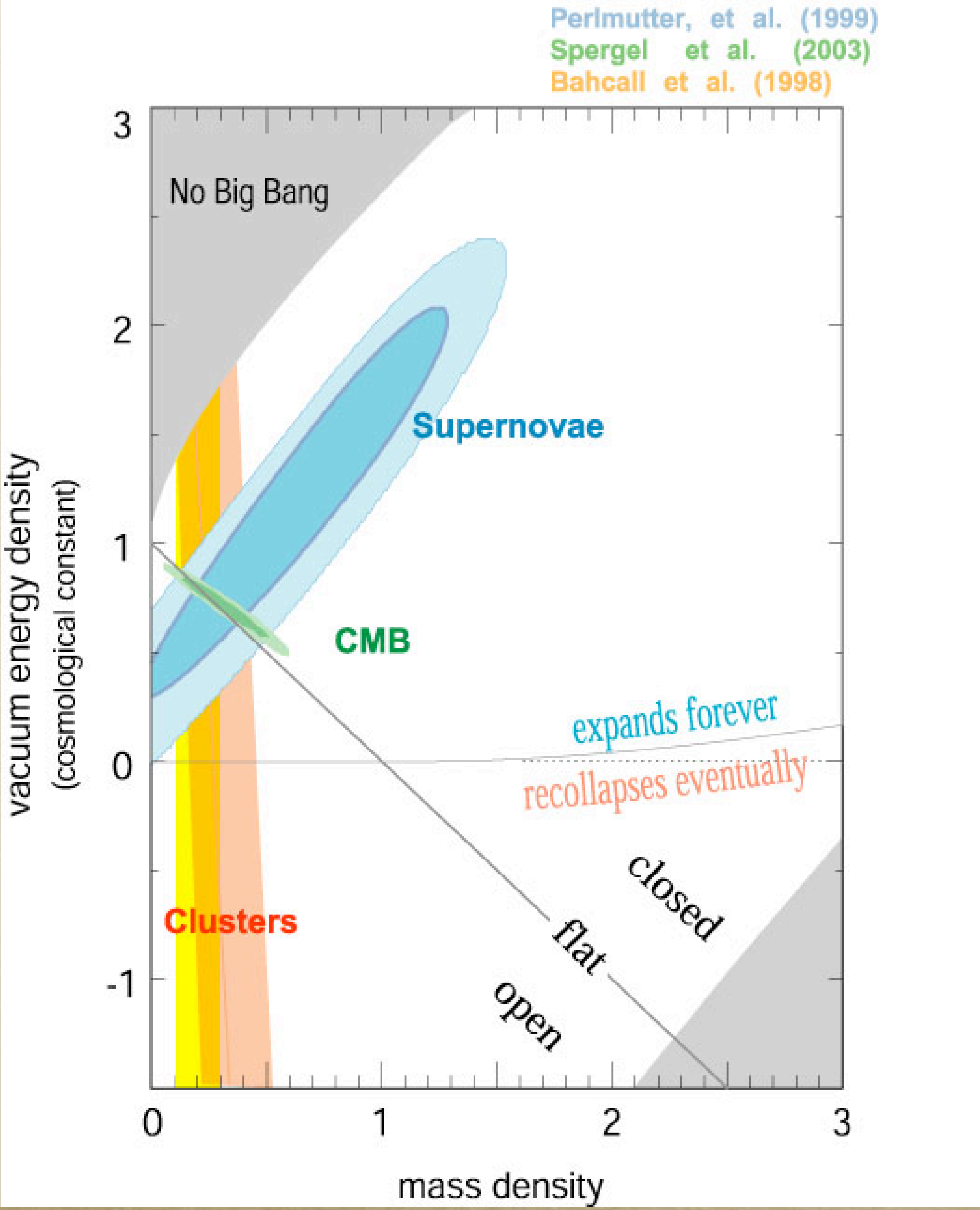
$$\begin{aligned} d(z) &= \int_0^z \frac{dz'}{H(z';\Omega_X, w_0, w_a)}; k=0 \\ &= \sin^{-1}\left(\int_0^z \frac{dz'}{H(z';\Omega_X, w_0, w_a)}\right); k=1 \\ &= \sinh^{-1}\left(\int_0^z \frac{dz'}{H(z';\Omega_X, w_0, w_a)}\right); k=-1 \end{aligned}$$

Supernova Results





Concordance



Implications of an Accelerating Universe

- *The ene... dominated*

- **"Why now?"**

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

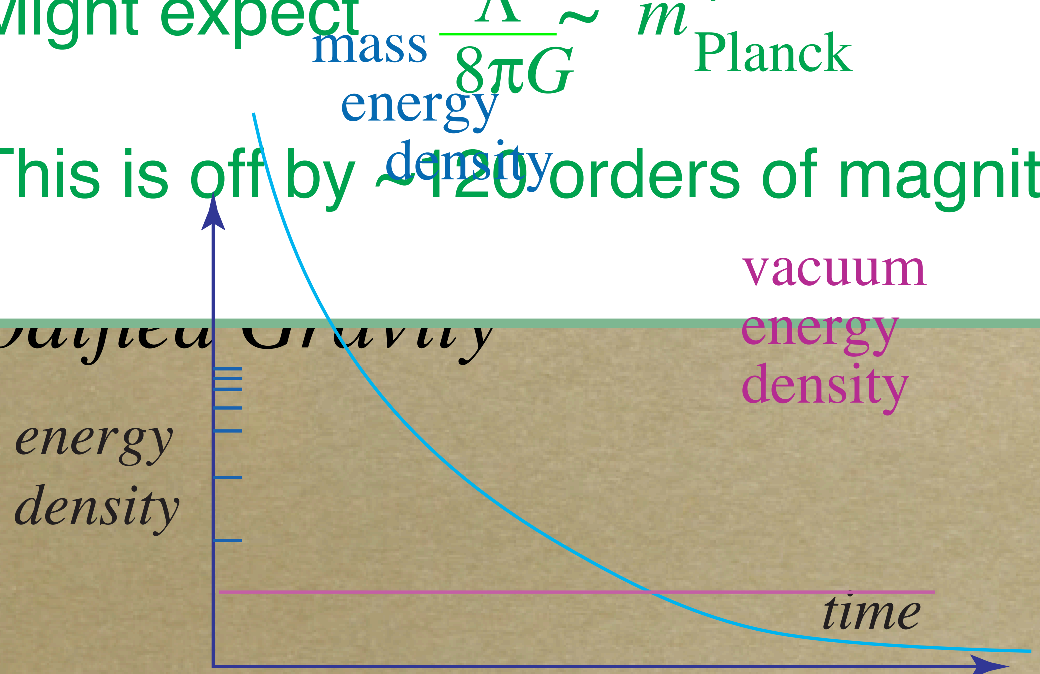
MATTER:	$p = 0$	$\longrightarrow$	$\rho \propto R^{-3}$
VACUUM ENERGY:	$p = -\rho$	$\longrightarrow$	$\rho \propto constant$

- **Why...**

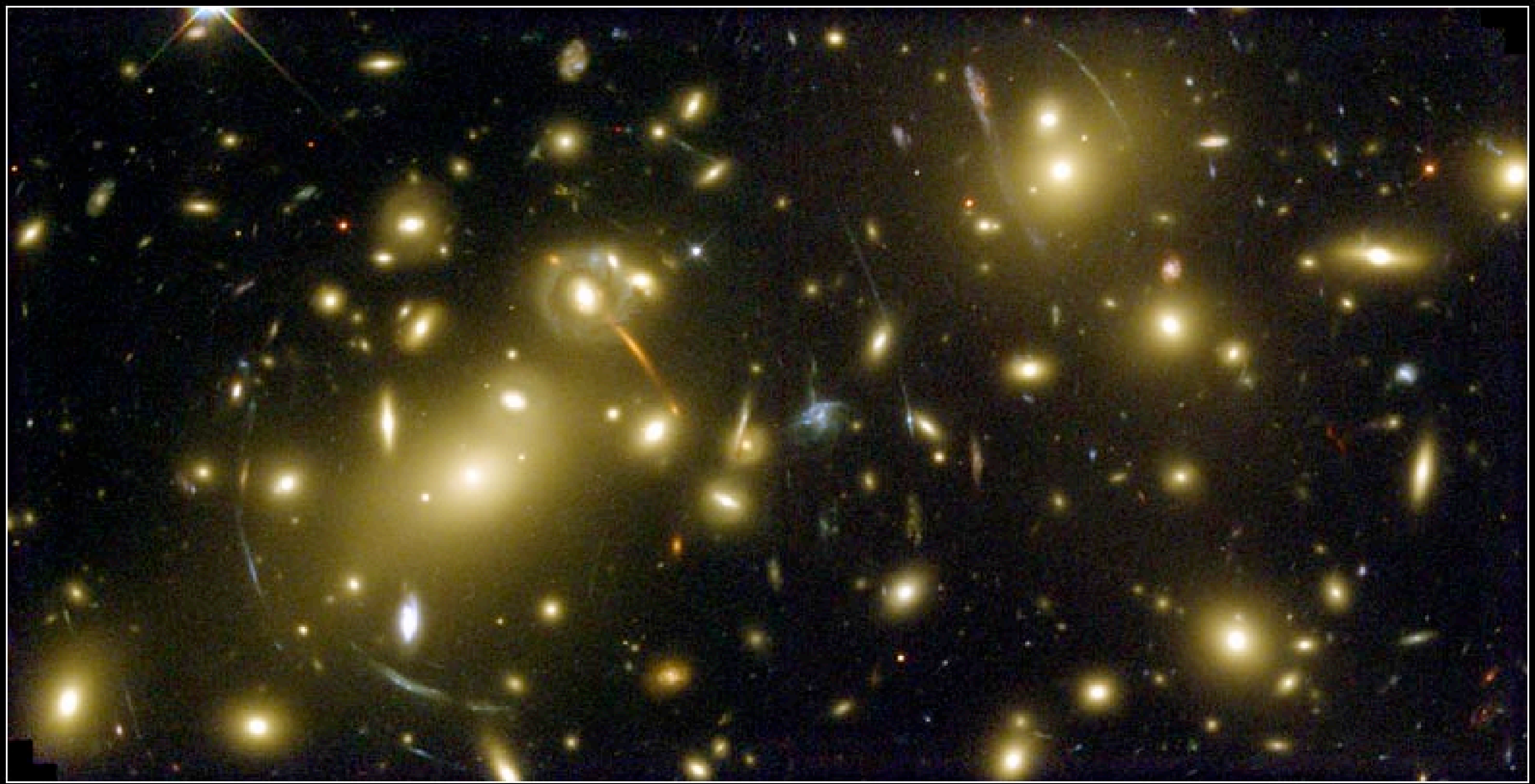
Might expect $\dfrac{\Lambda}{8\pi G} \sim m^{4}_{\text{Planck}}$

This is off by ~120 orders of magnitude!

- *Modified Gravity*



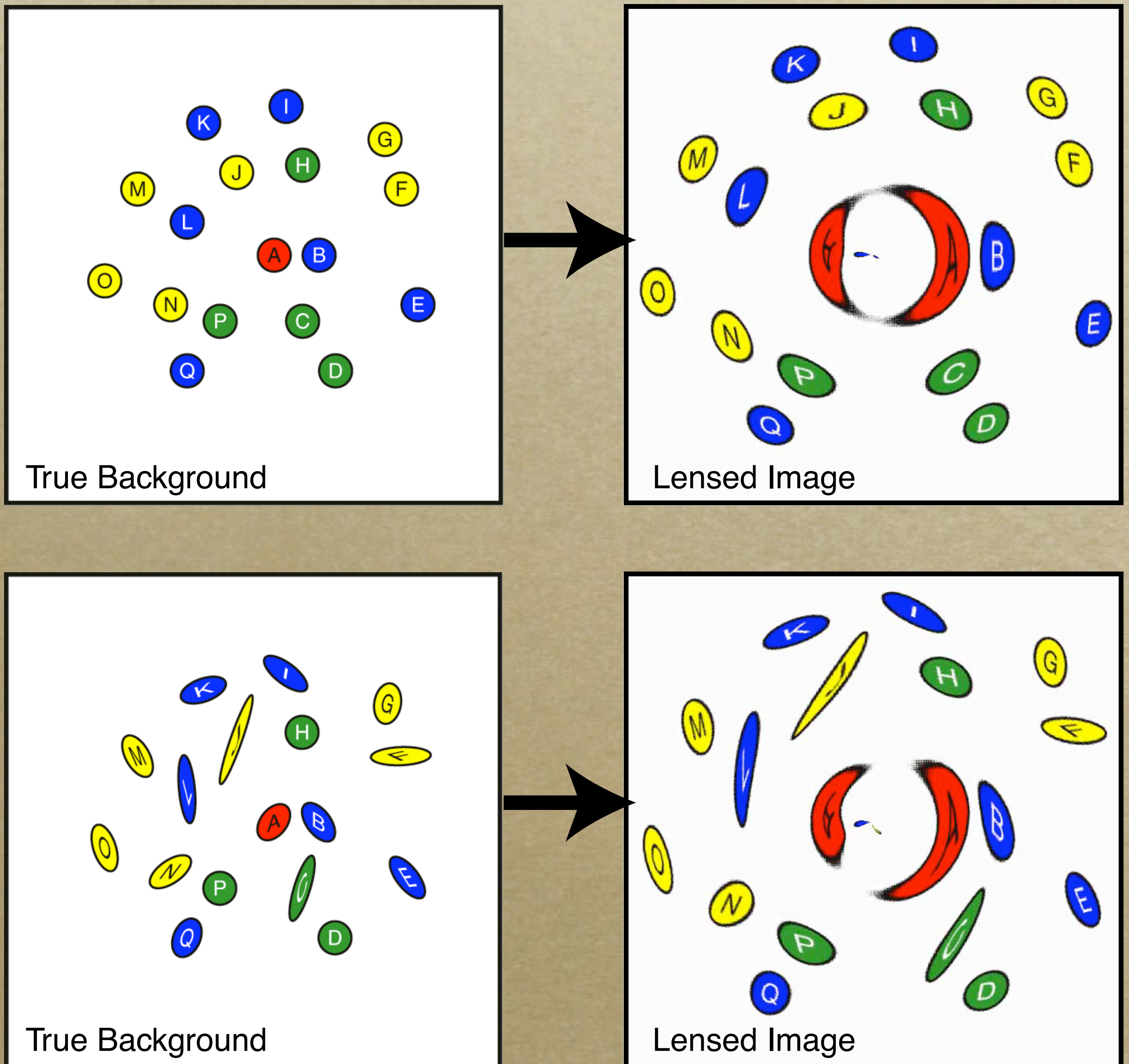
Gravitational Lensing



Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

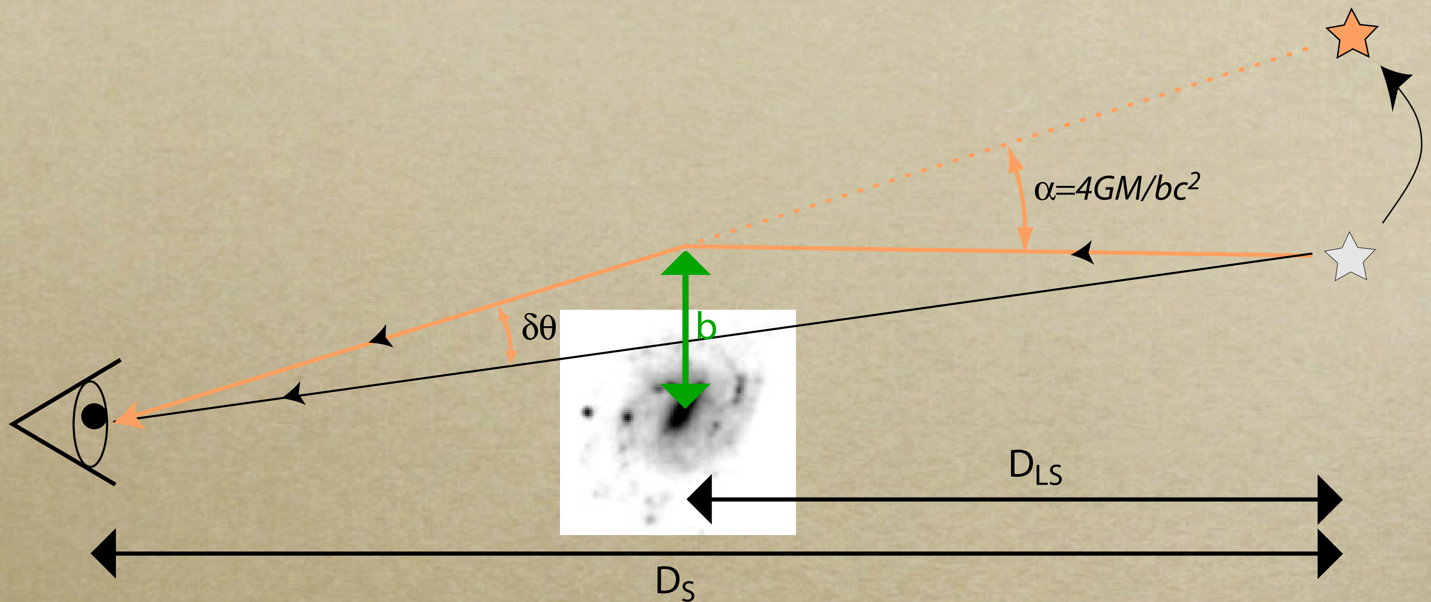
Review of Weak Lensing



Weak lensing requires the measurement of many galaxy shapes to extract average trends

Courtesy of Gary Bernstein

Dark Energy Signals in the WL Sky



$$\delta\theta = \frac{4GM}{bc^2} \quad \frac{D_{LS}}{D_S}$$

We observe this deflection angle (more precisely, gradients of the deflection angle).

Cosmology changes growth rate of mass structures in the Universe.

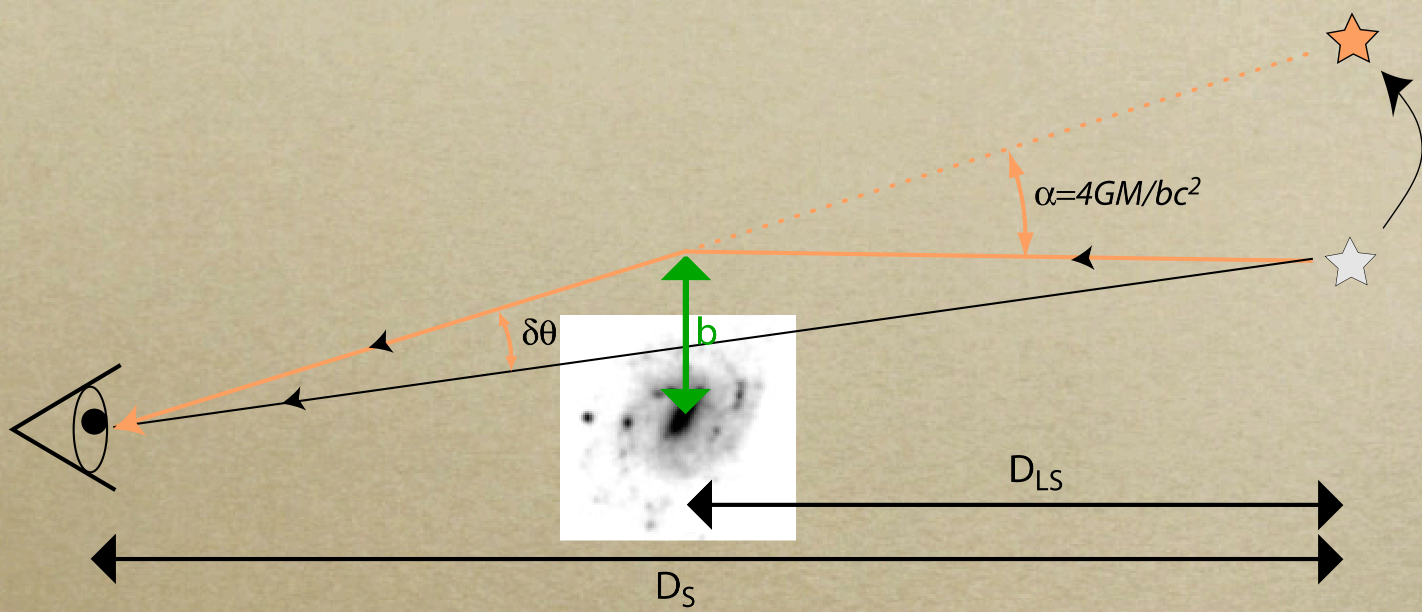
Cosmology changes the geometric distance factors.

Courtesy of Gary Bernstein

Redshift to Distance

$$
\begin{aligned}
d(z) &= \int_0^z \frac{dz'}{H(z';\Omega_X, w_0, w_a)}; k = 0 \\
&= \sin^{-1}\left(\int_0^z \frac{dz'}{H(z';\Omega_X, w_0, w_a)}\right); k = 1 \\
&= \sinh^{-1}\left(\int_0^z \frac{dz'}{H(z';\Omega_X, w_0, w_a)}\right); k = -1
\end{aligned}
$$

Dark Energy Signals in the WL Sky



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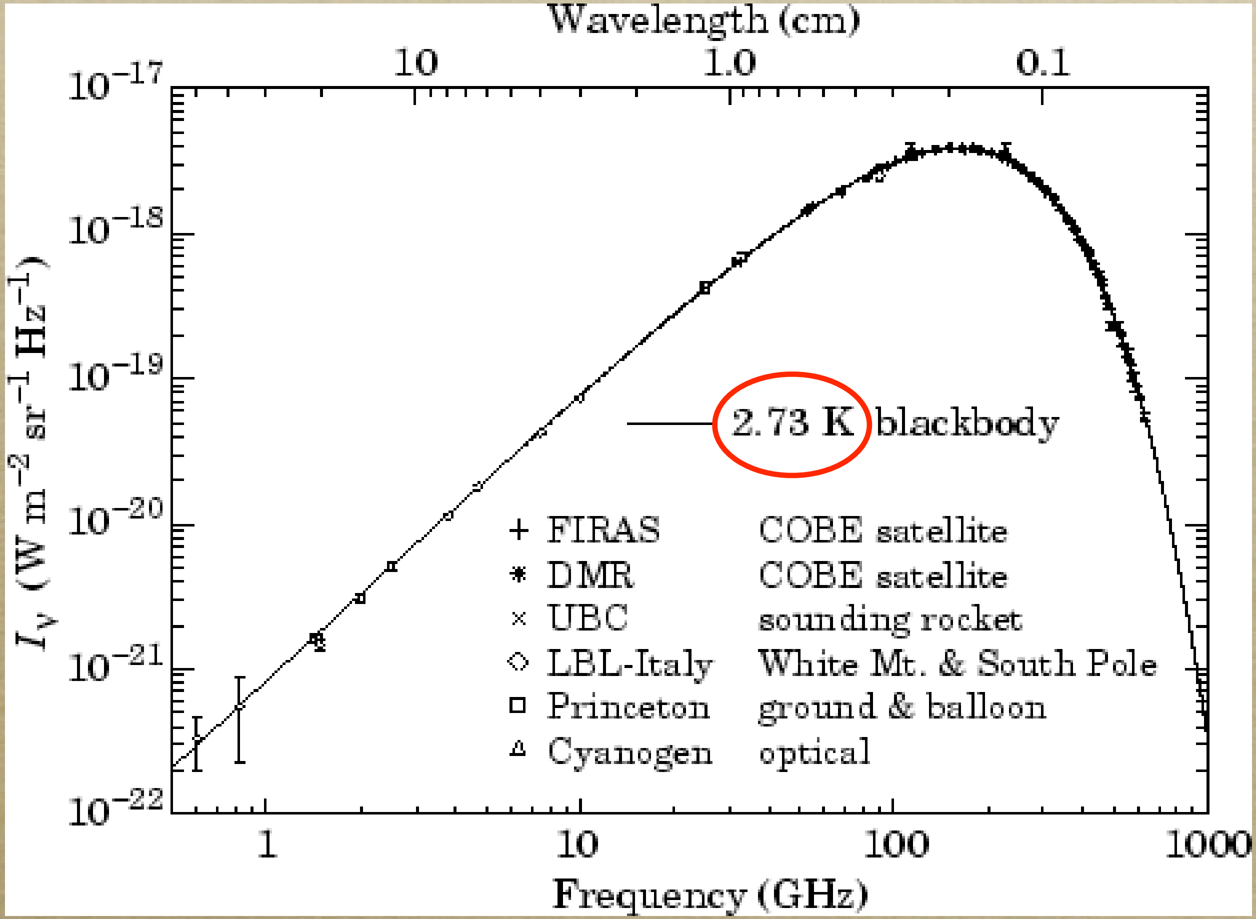
Mass fluctuations that produce lensing

Cosmic Microwave Background

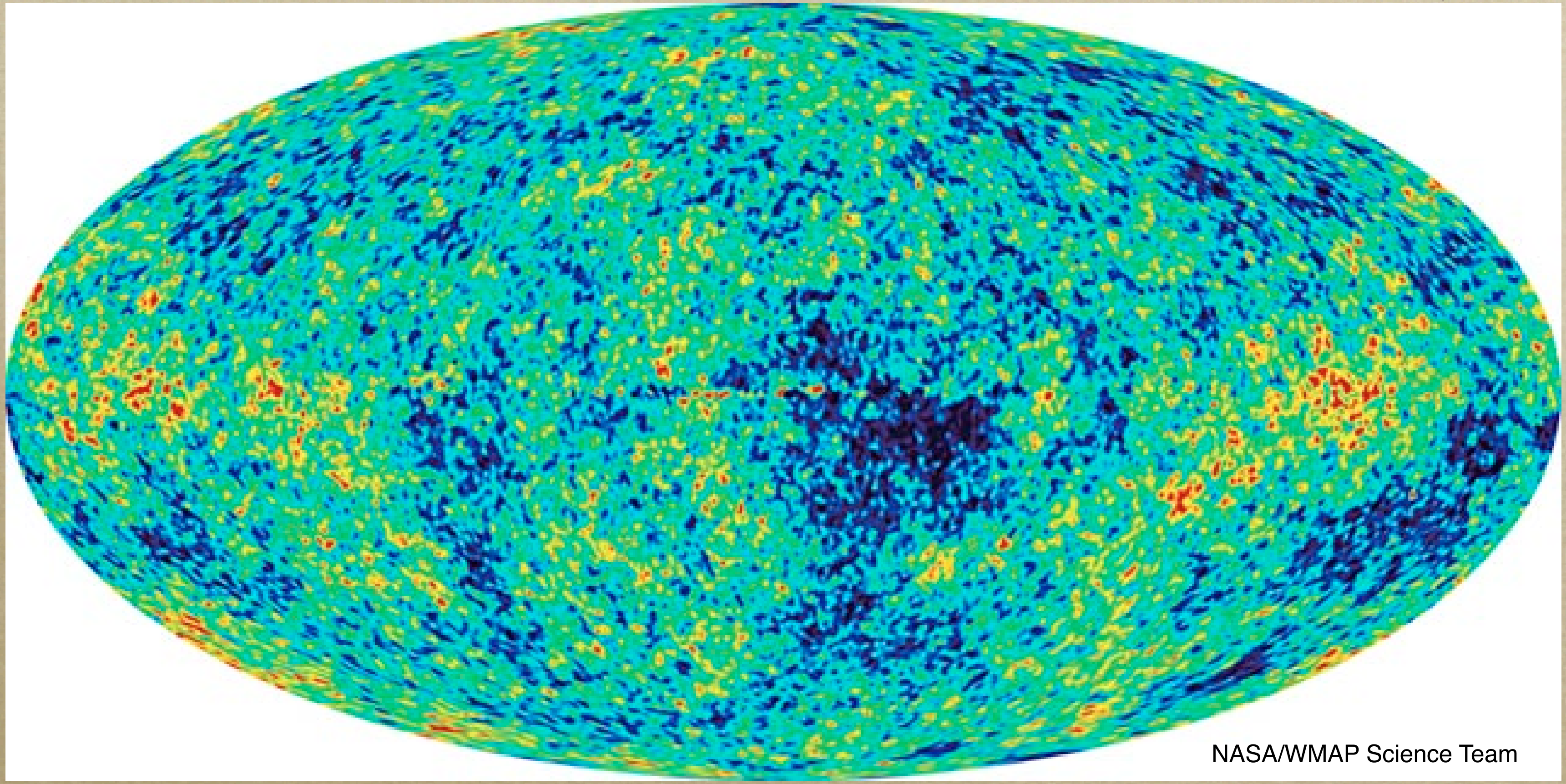
- *Universe is filled with radiation*



Thermal Universe

- *The Universe used to be a lot hotter*
  - $T \propto a^{-1}$*adiabatically expanding Universe*
  - *The Universe was a plasma of protons, electrons, and photons*
  - *At z~1000 (T~3000 K) neutral Hydrogen formed (recombination) - photons no longer coupled to matter*
  - *CMB photons streaming to us from the surface of last scattering*

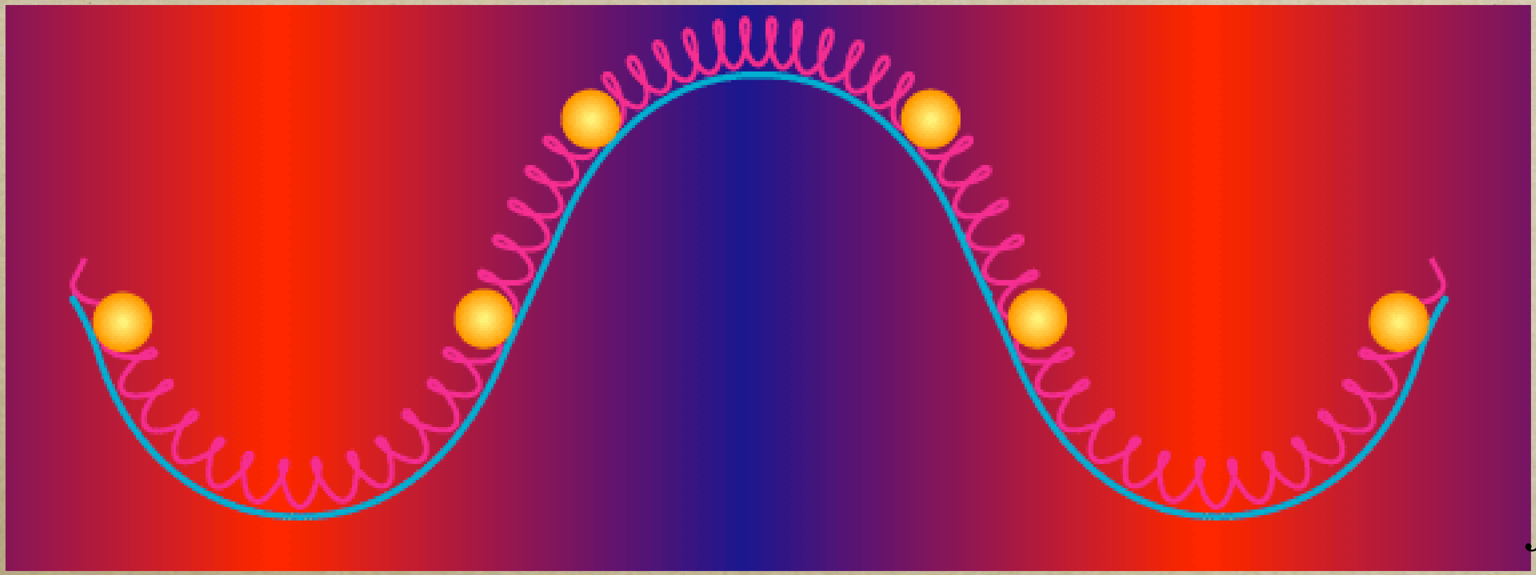
Temperature Map



- *Precision measurements show Temperature fluctuations*

$$\frac{dT}{T} \sim 10^{-5}$$

Temperature Fluctuations = Energy Density Fluctuations



from Hu

- *Temperature fluctuations are due to energy density fluctuations* ($\delta = d\rho/\rho$)
  - *Acoustic compression*
  - *Gravitational redshift*
  - *Doppler effect*

Density Fluctuations Grow

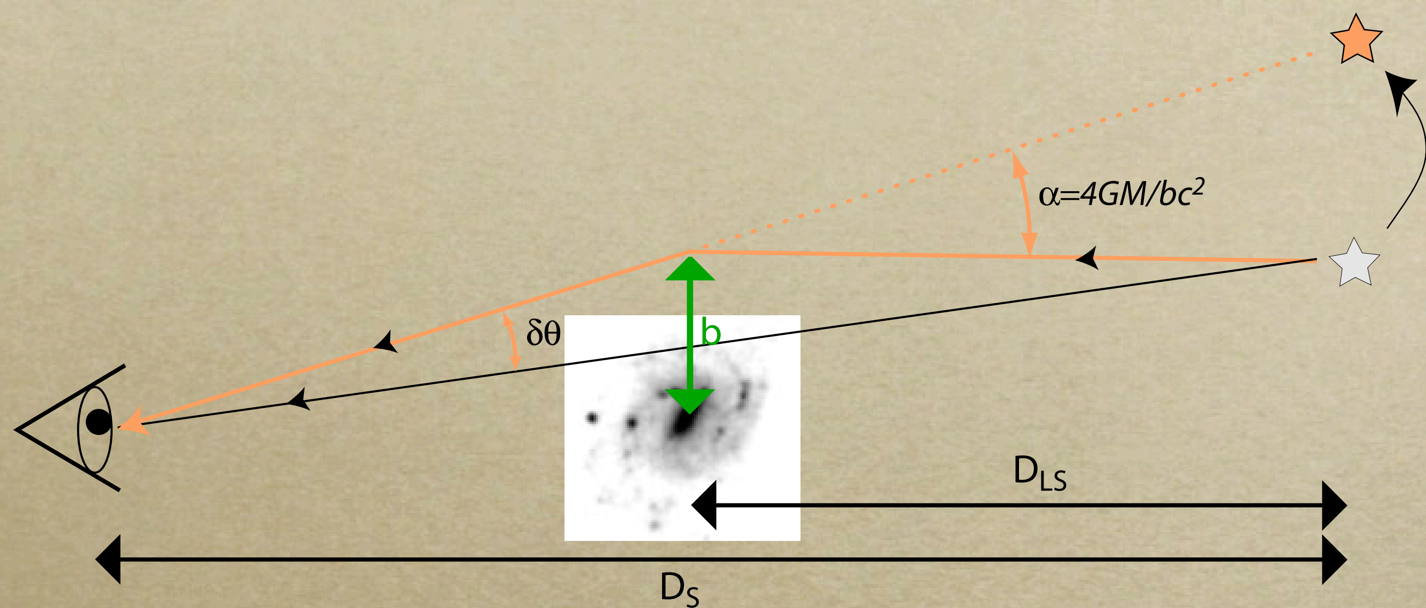
- *Radiation pressure turns off after recombination, matter is free to cluster gravitationally*
- *Evolution of density perturbations*

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

$$\ddot{\delta} + 2H(z;\Omega_X, w_0, w_a)\dot{\delta} - \frac{3}{2}\Omega(z)H^2(z;\Omega_X, w_0, w_a)\delta = 0$$

CMB as an initial condition + dark-energy-dependent clustering characterize the lensing mass

Dark Energy Signals in the WL Sky



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Cosmology changes growth rate of mass structures in the Universe.

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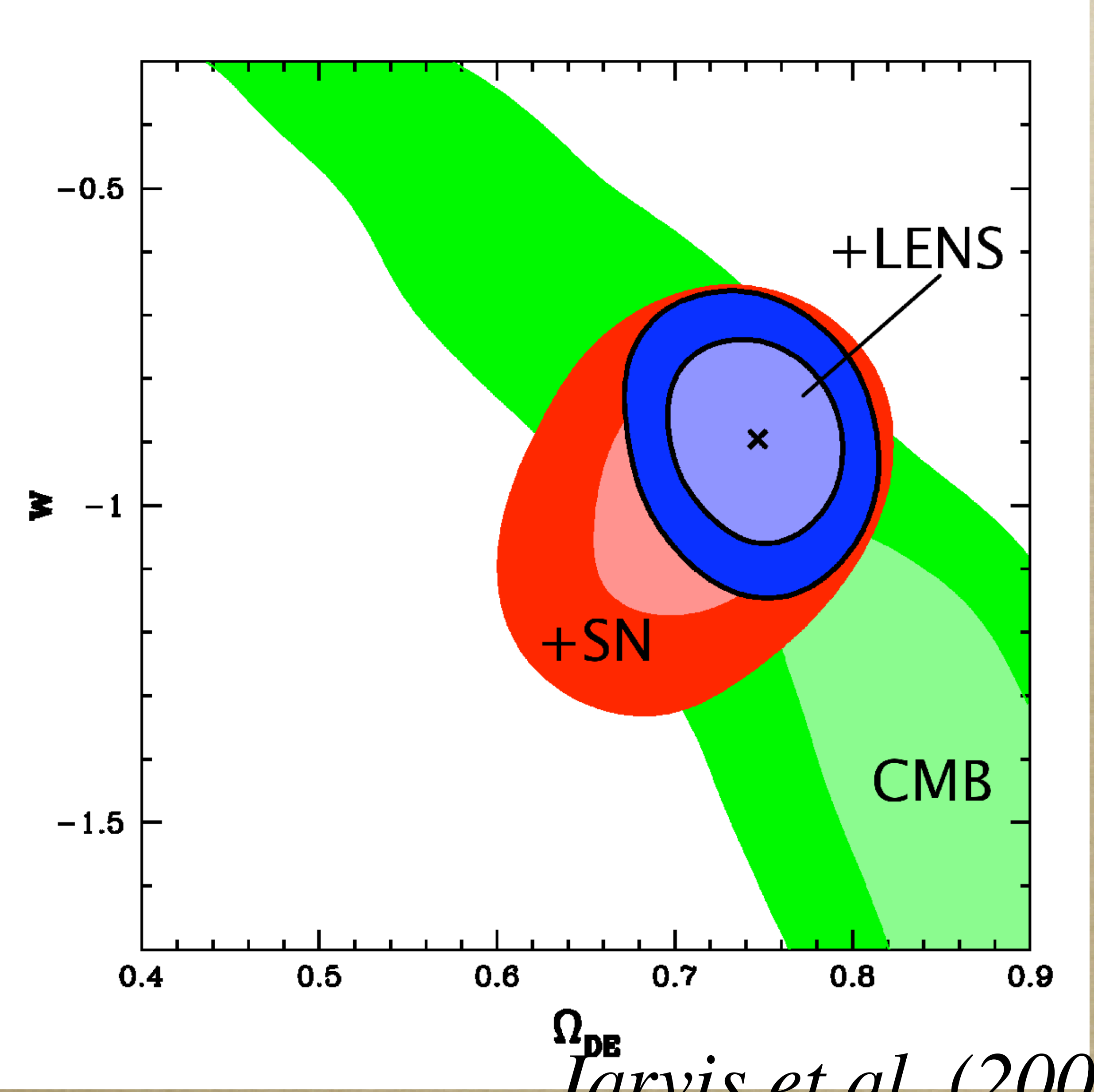
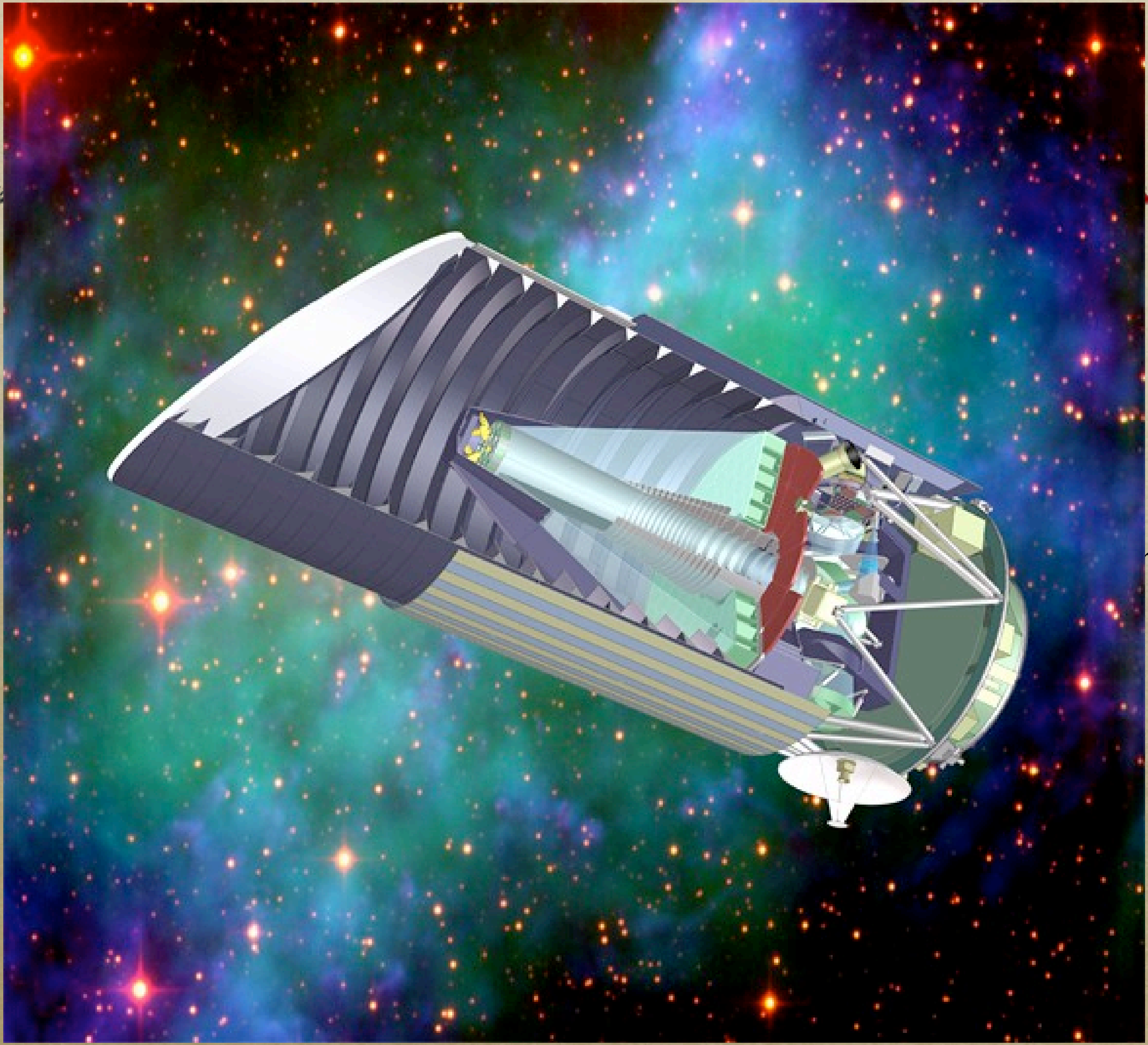
Courtesy of Gary Bernstein

Dark Energy Lensing Results

From a 75 square degree survey from CTIO



Jarvis et al. (2005)



SNAP Collaboration

LBNL	G. Aldering, S. Bailey, C. Bebek, W. Carithers, T. Davis†, K. Dawson, C. Day, R. DiGennaro, S. Deustua†, D. Groom, M. Hoff, S. Holland, D. Huterer†, A. Karcher, A. Kim, W. Kolbe, W. Kramer, B. Krieger, G. Kushner, N. Kuznetsova, R. Lafever, J. Lamoureux, M. Levi, S. Loken, B. McGinnis, R. Miquel, P. Nugent, H. Oluseyi†, N. Palaio, S. Perlmutter, N. Roe, H. Shukla, A. Spadafora, H. Von Der Lippe, J-P. Walder, G. Wang
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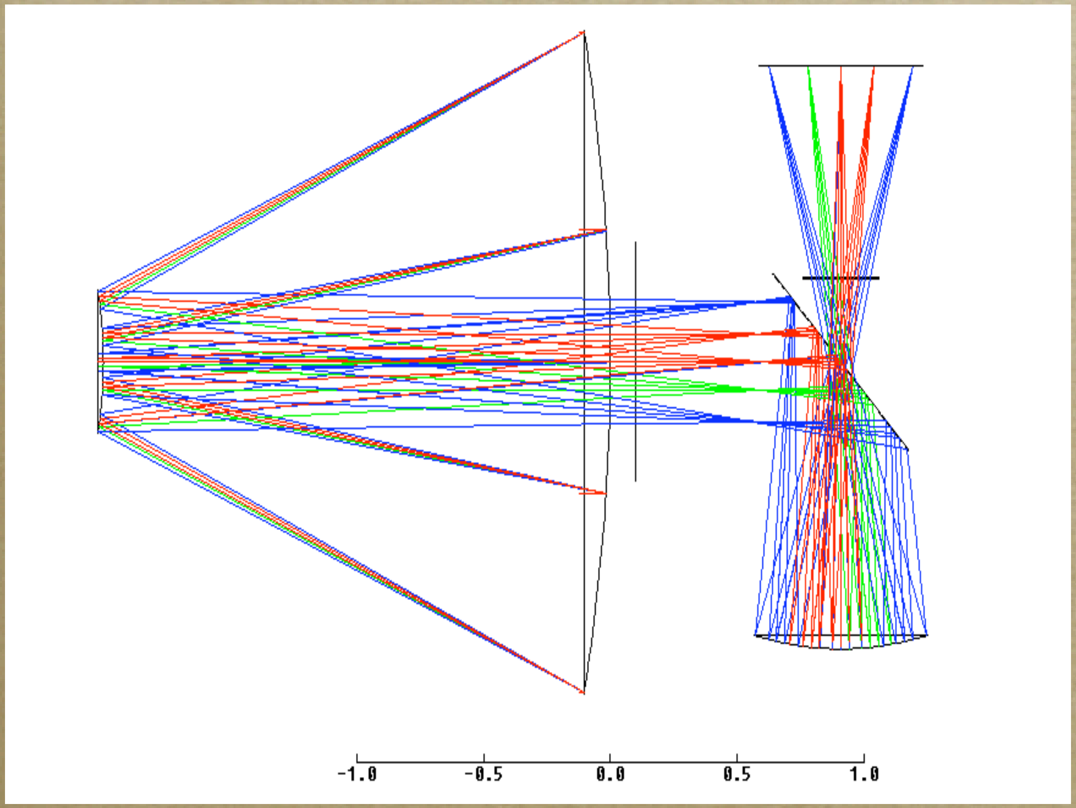
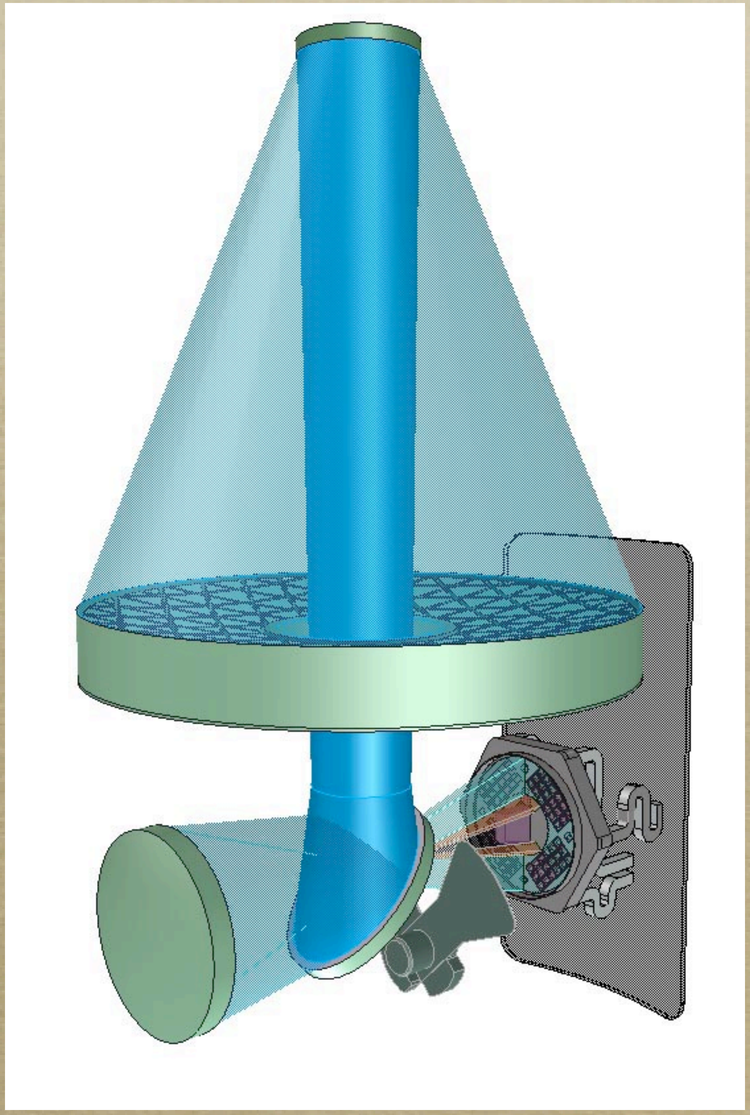
Fermi National Laboratory	J. Annis, F. DeJongh, S. Dodelson, T. Diehl, J. Frieman, D. Holz†, L. Hui, S. Kent, P. Limon, J. Marriner, H. Lin, J. Peoples, V. Scarpine, A. Stebbins, C. Stoughton, D. Tucker, W. Wester
Indiana U.	C. Bower, N. Mostek, J. Musser, S. Mufson
IN2P3-Paris -Marseille	P. Astier, E. Barrelet, R. Pain, G. Smadja†, D. Vincent A. Bonissent, A. Ealet, D. Fouchez, A. Tilquin
JPL	D. Cole, M. Frerking, J. Rhodes, M. Seiffert
LAM (France)	S. Basa, R. Malina, A. Mazure, E. Prieto
University of Michigan	B. Bigelow, M. Brown, M. Campbell, D. Gerdes, W. Lorenzon, T. McKay, S. McKee, M. Schubnell, G. Tarle, A. Tomasch
University of Pennsylvania	G. Bernstein, L. Gladney, B. Jain, D. Rusin
University of Stockholm	R. Amanullah, L. Bergström, A. Goobar, E. Mörtsell
SLAC	W. Althouse, R. Blandford, W. Craig, S. Kahn, M. Huffer, P. Marshall
STScI	R. Bohlin, D. Figer, A. Fruchter

snap.lbl.gov

SNAP Telescope

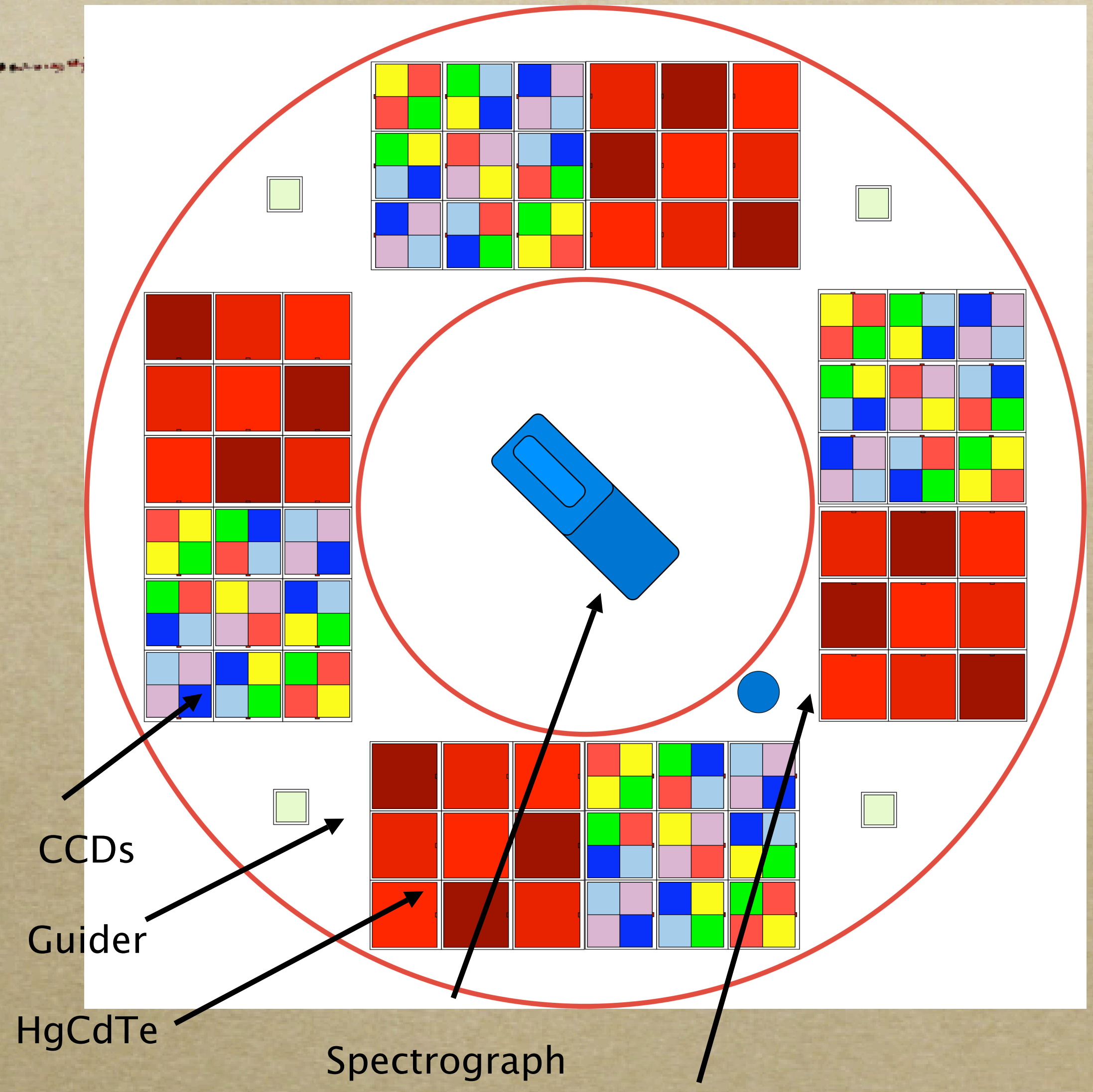
- *2-m primary aperture, 3-mirror anastigmatic design.*
- *Provides a wide-field flat focal plane.*





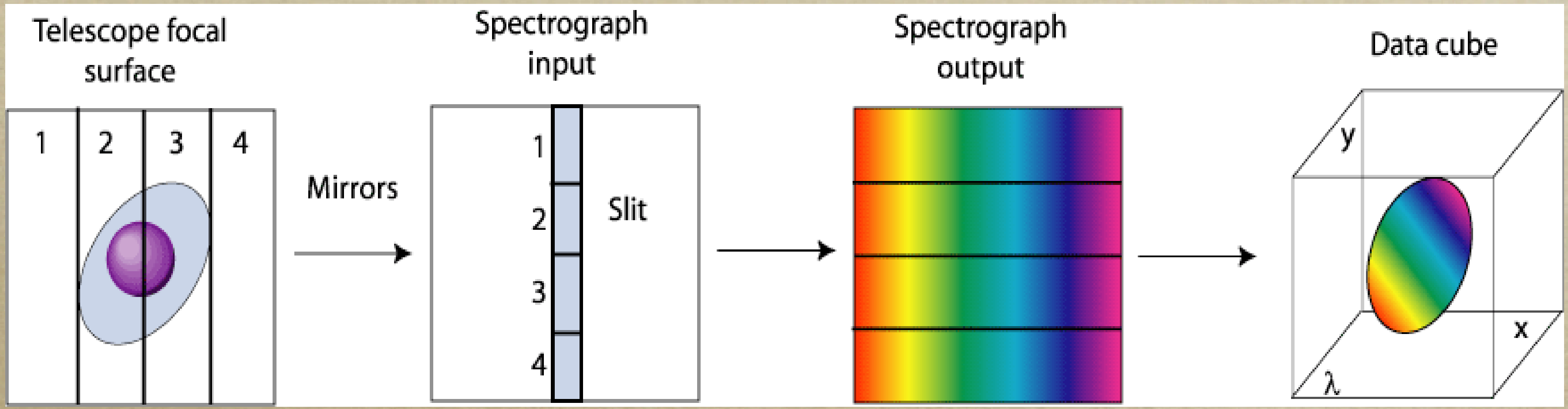
Instrumentation: Imager

- A large solid-angle camera (0.7 square degrees) provides multiplexed supernova discovery and followup.
- Covers wavelength region of interest, 0.35- 1.7 microns.
- Fixed filter mosaic on top of the imager sensors.
  - 3 NIR bandpasses.
  - 6 visible bandpasses.
- Coalesce all sensors at one focal plane.
  - 36 2k x 2k HgCdTe NIR sensors covering 0.9-1.7 µm.
  - 36 3.5k x 3.5k CCDs covering 0.35–1.0 µm



r_{in}=6.0 mrad; r_{out}=13.0 mrad
r_{in}=129.120 mm; r_{out}=283.564 mm

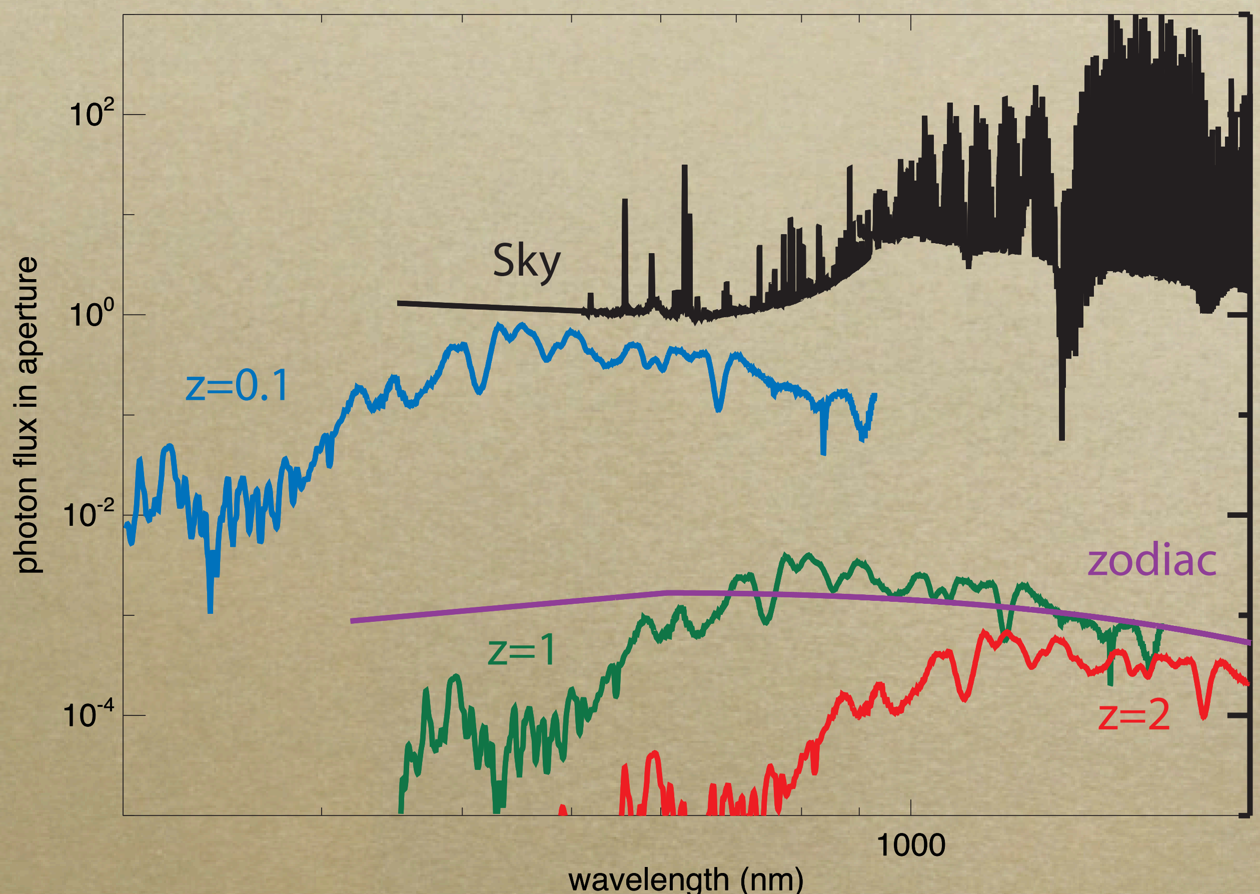
Spectrograph



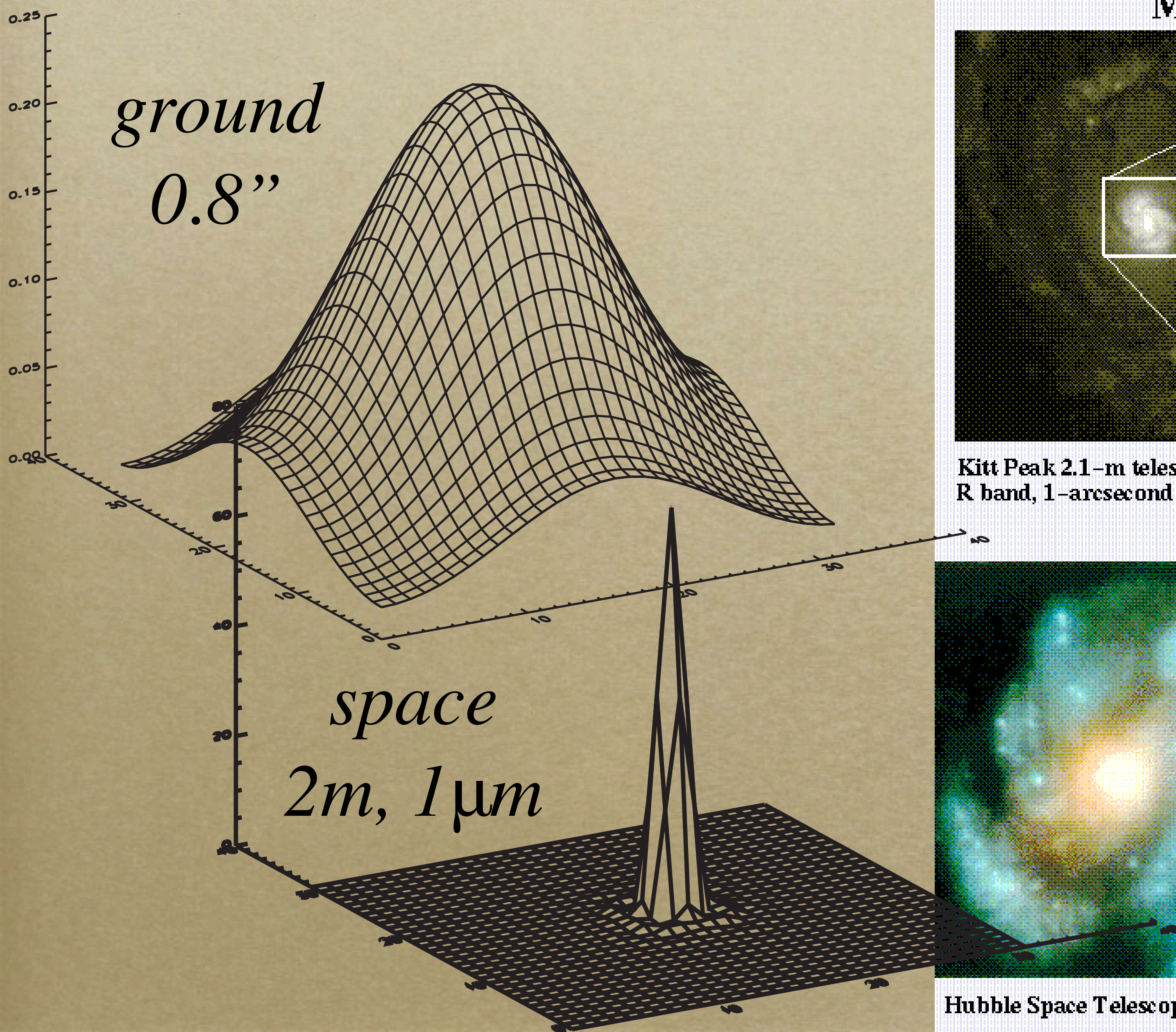
- *Integral field unit based on an imager slicer- Data cube.*
- *Input aperture is 3" x 3" – reduces pointing accuracy requirement*
- *Simultaneous SNe and host galaxy spectra.*
- *Internal beam split to visible and NIR.*

Why Space?

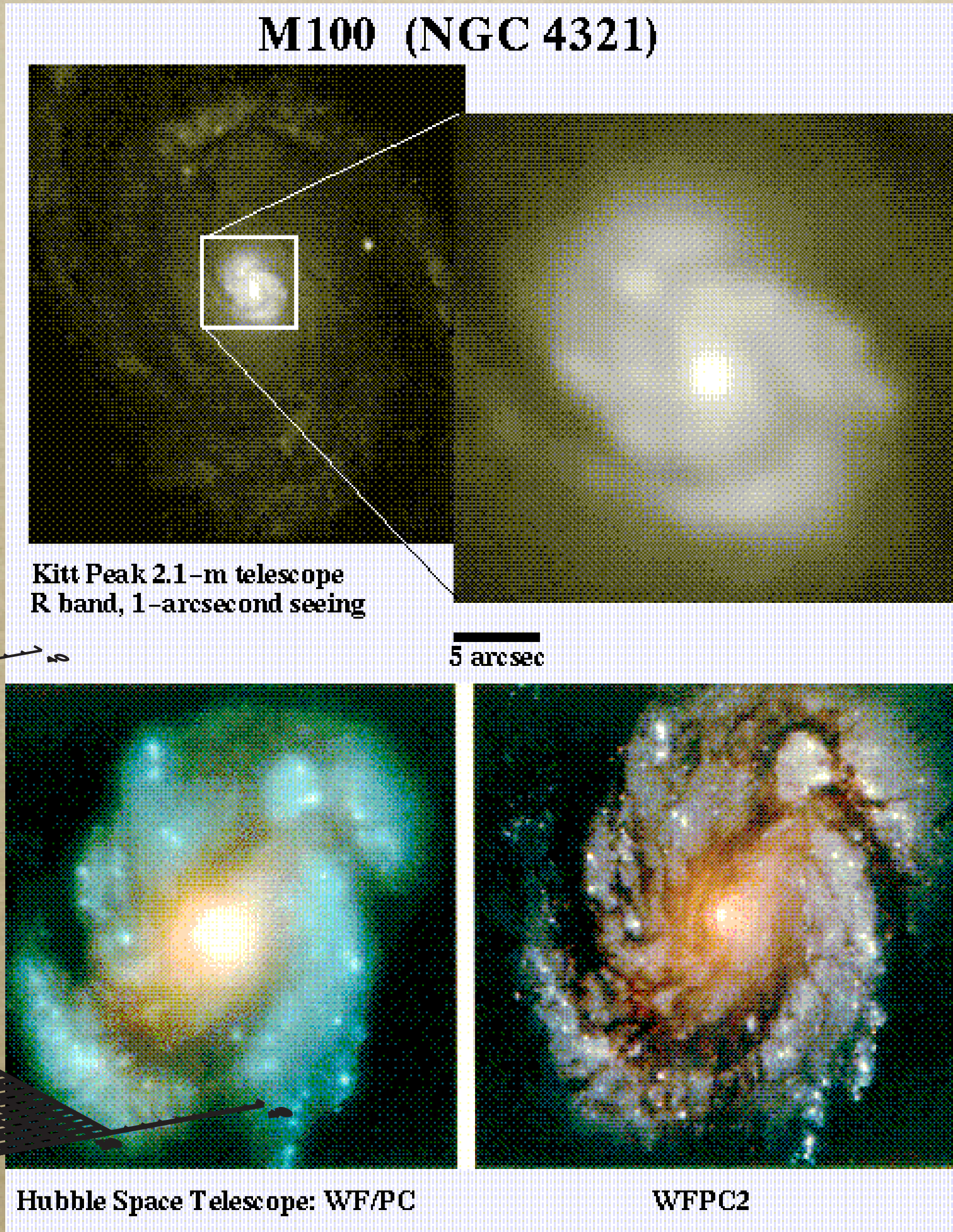
Sky emission the dominant source of noise



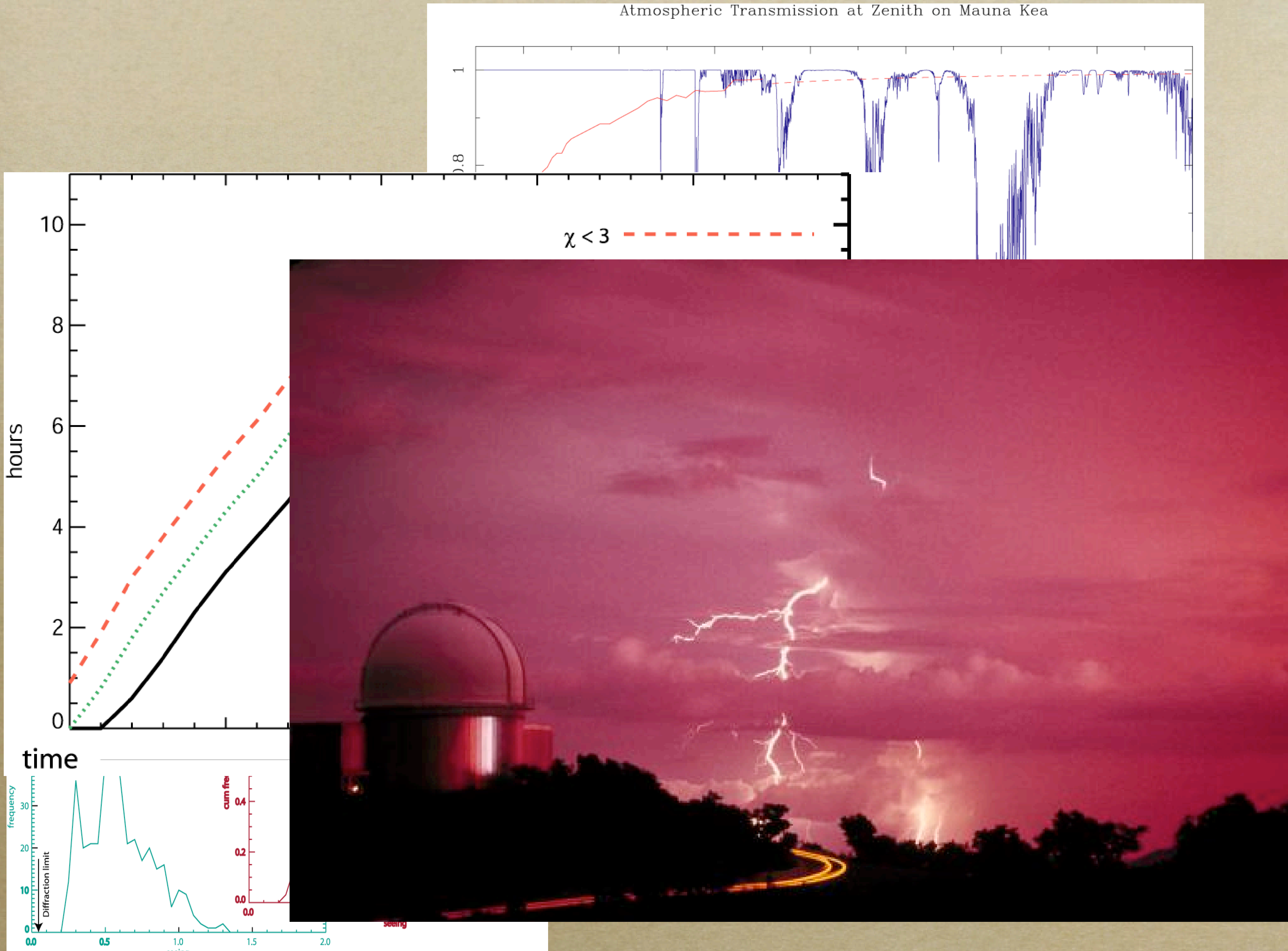
Resolution



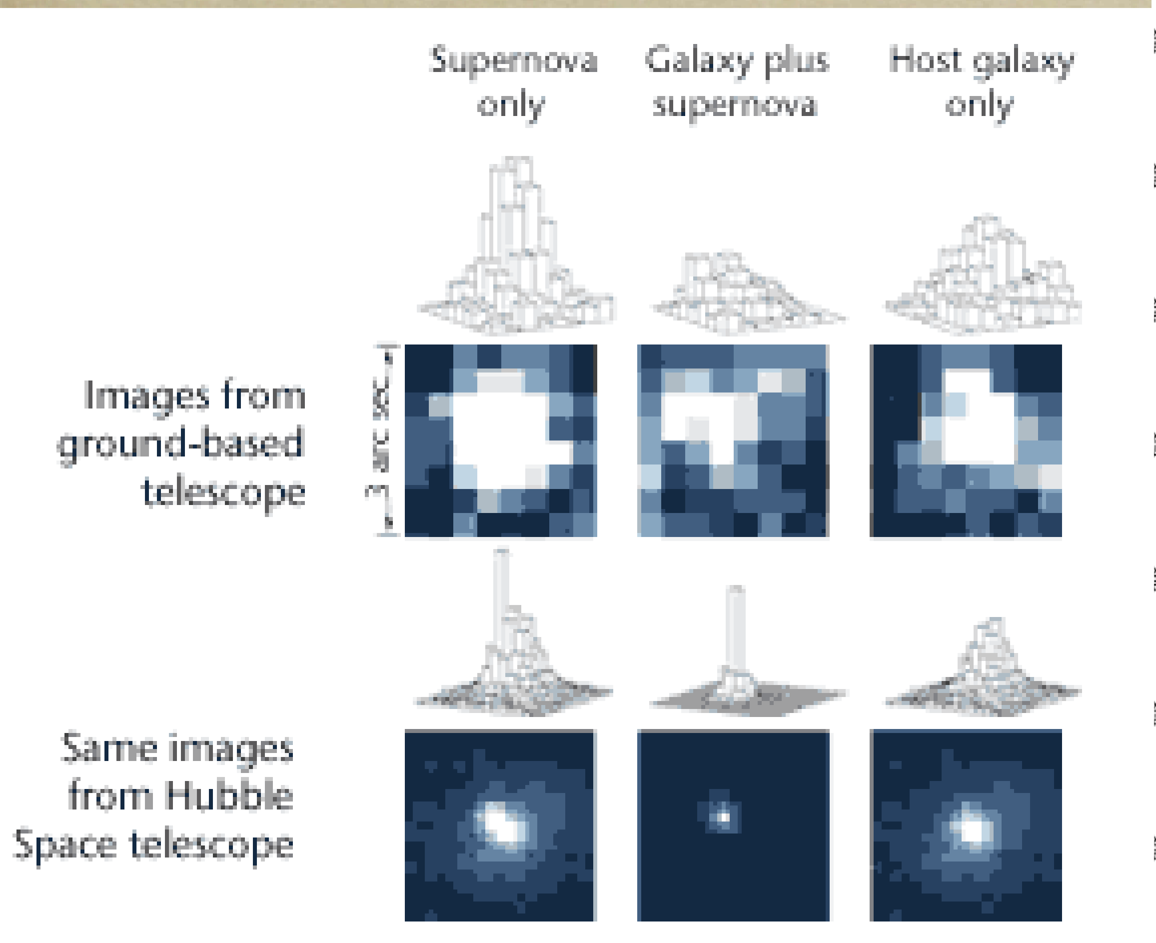
ground
0.8”
space
2m, 1µm



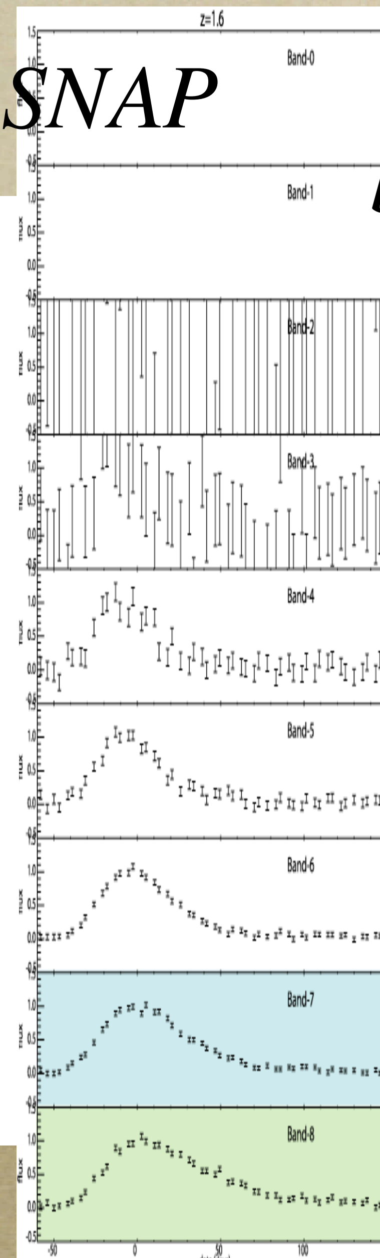
M100 (NGC 4321)
Kitt Peak 2.1-m telescope
R band, 1-arcsecond seeing
5 arcsec
Hubble Space Telescope: WF/PC
WFPC2


Atmospheric Transmission at Zenith on Mauna Kea
1
10
8
6
4
2
0
hours
χ < 3
time
frequency
30
20
10
0
Diffraction limit
0.0
0.5
1.0
1.5
2.0
seeing
0.4
0.2
0.0

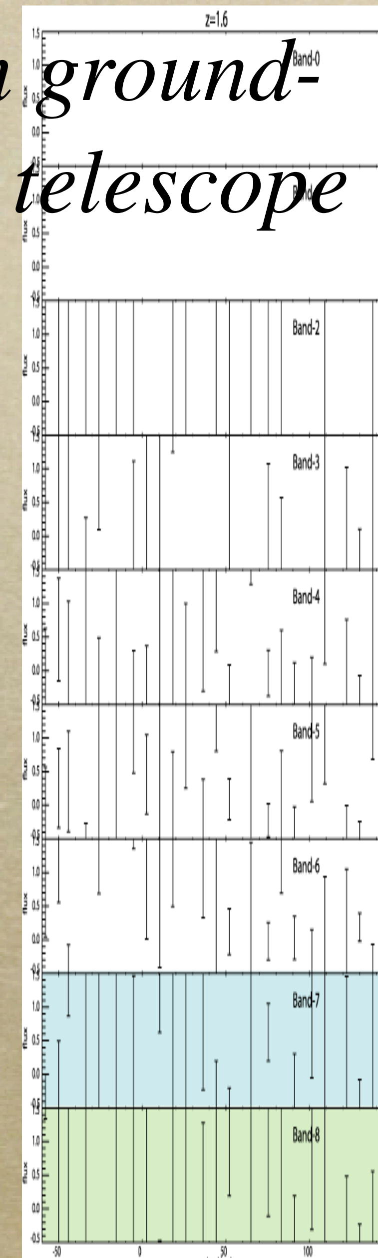
Simulated Light Curves



SNAP



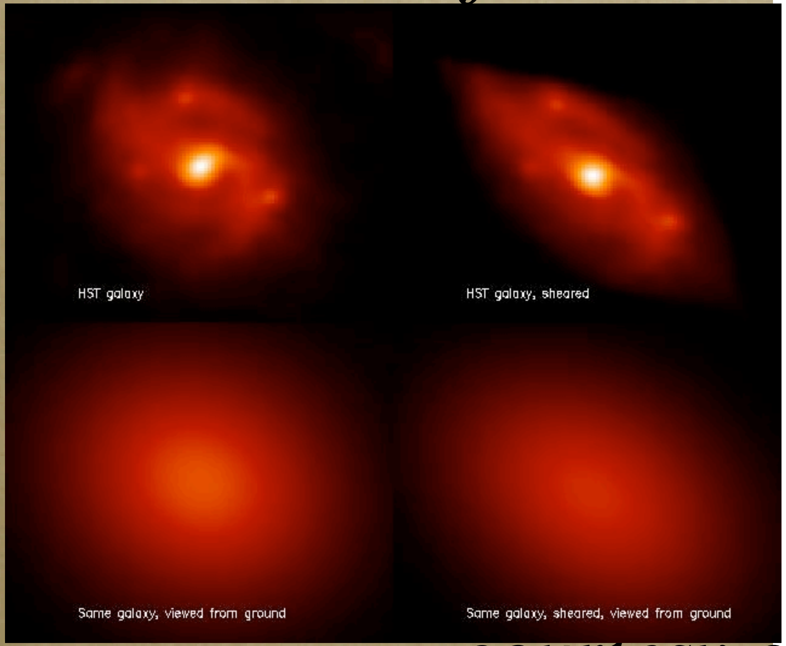
6.5-m ground-based telescope

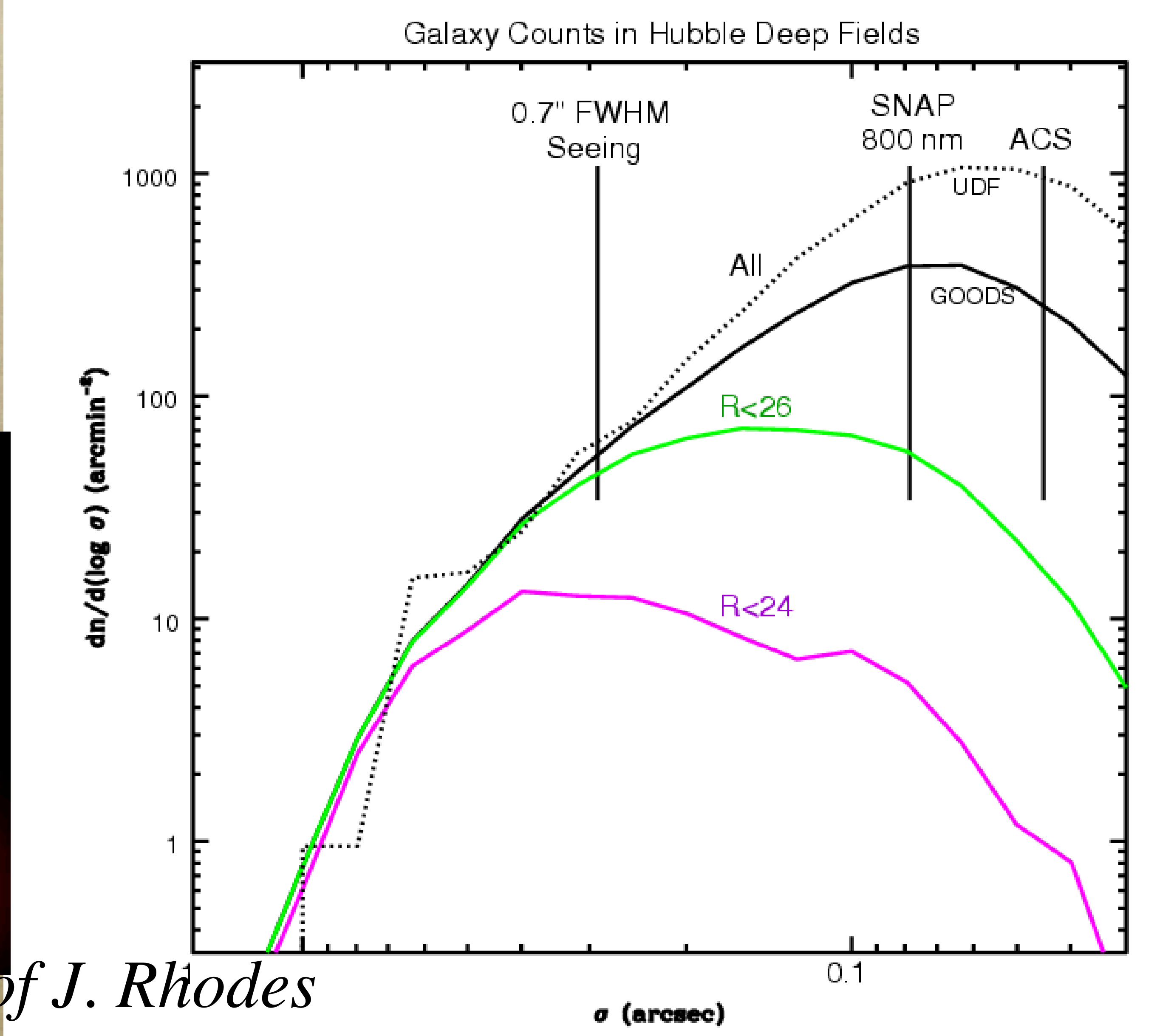


z=1.6

PSF Number counts vs size

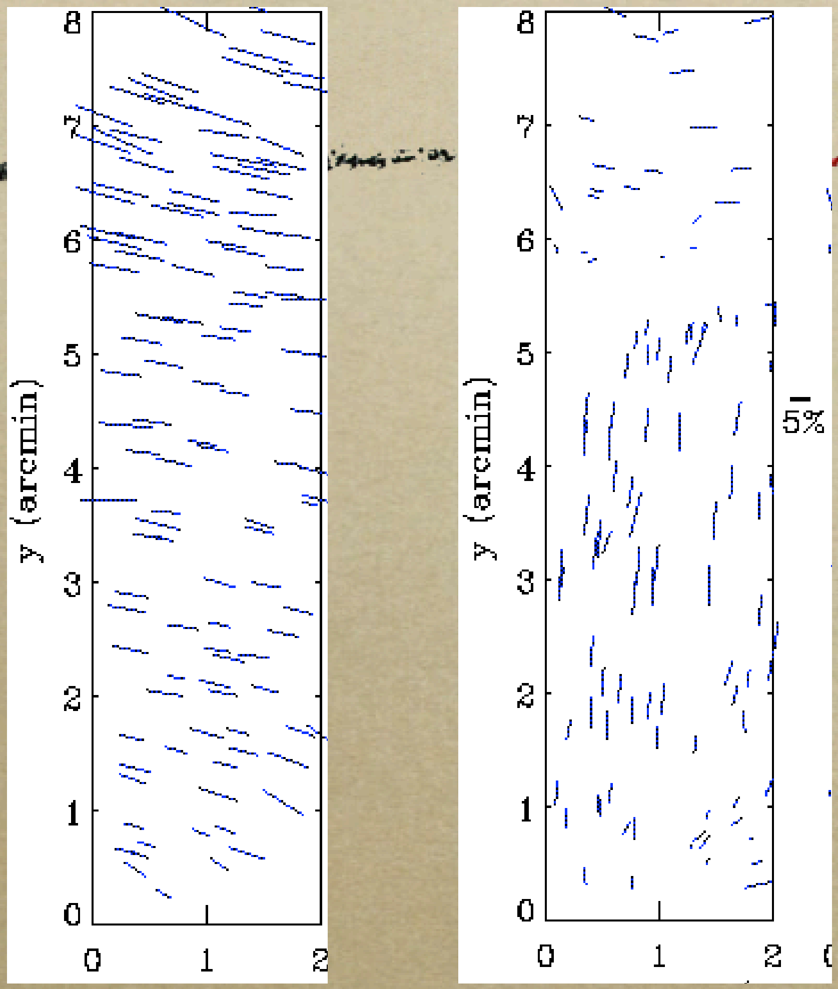
Finer PSF resolves more galaxies at higher redshifts





courtesy of J. Rhodes

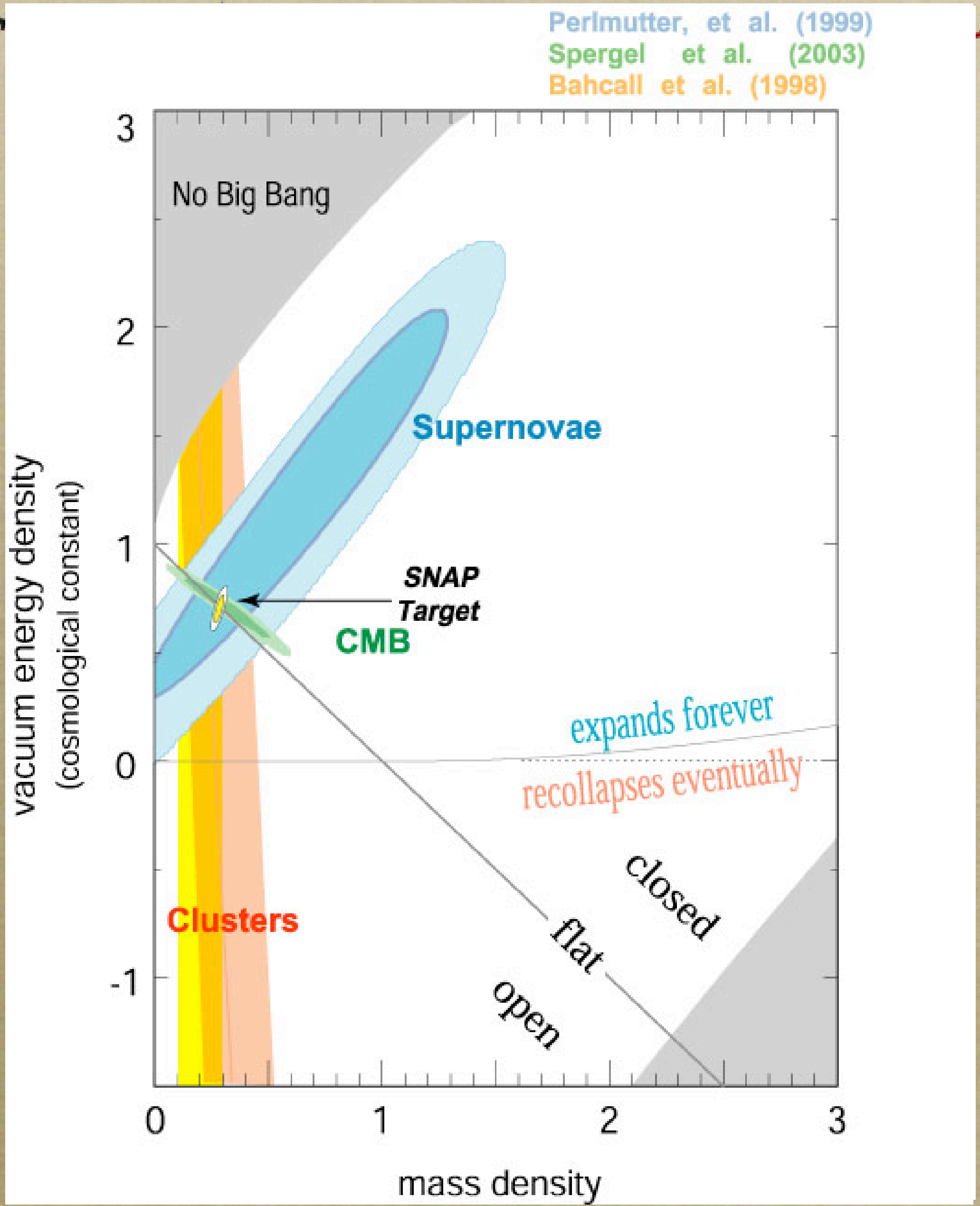
PSF Instability



courtesy of J. Rhodes

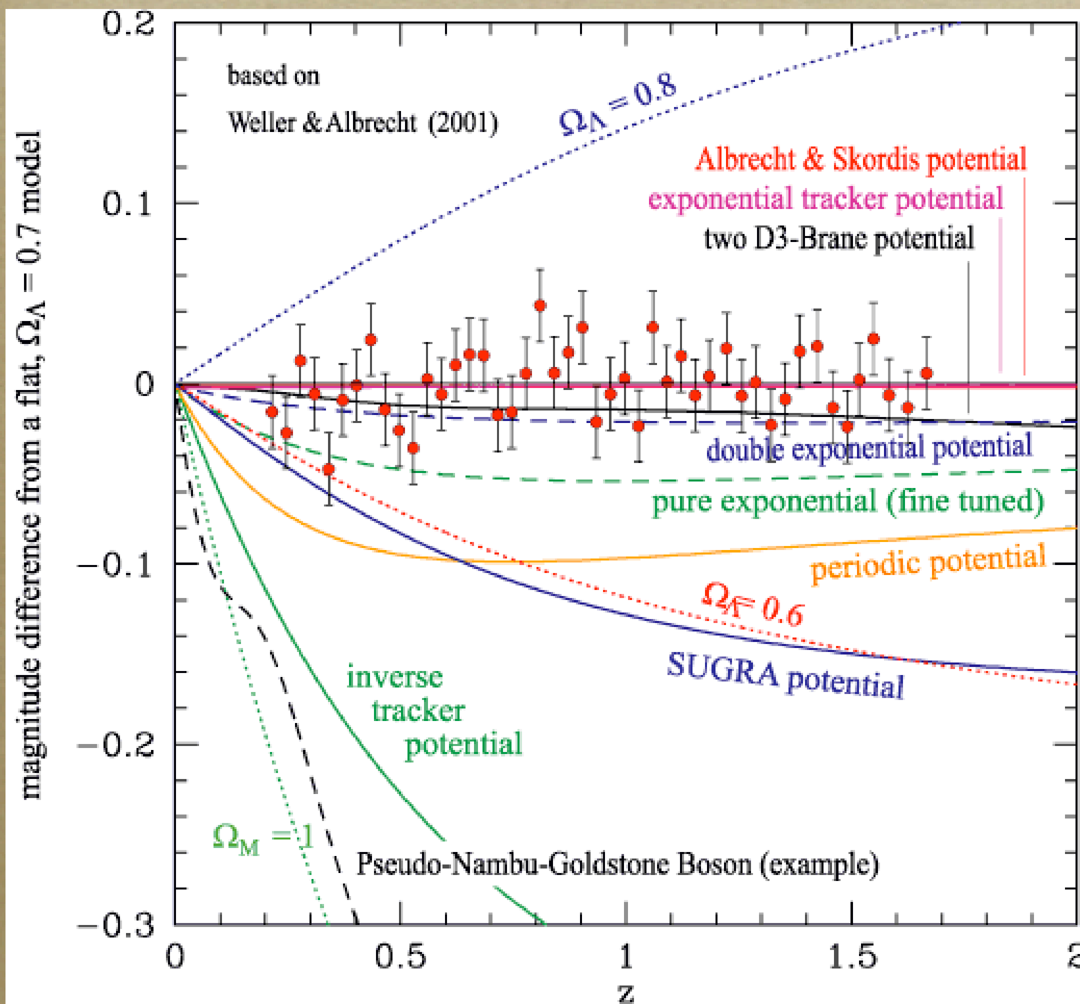
2 PSF maps taken minutes apart on Keck. The pattern of PSF anisotropy has changed dramatically. Corrections on scales smaller than the star-star separation are not possible. This is likely a fundamental limit from the ground due to thermal instability.

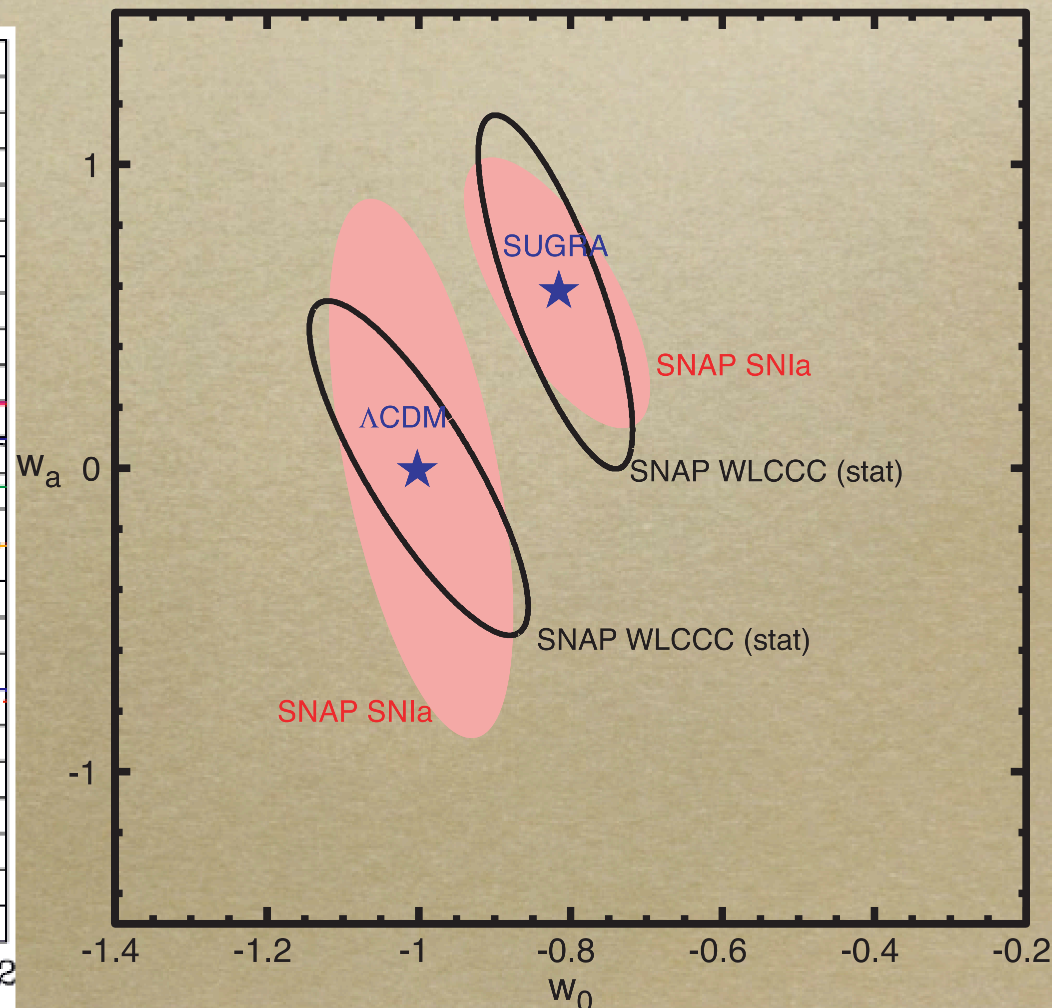
Cosmological Parameter Determination



Cosmological Parameter Determination

- Shown is the w_0,w' confidence region of this Monte Carlo realization of the SNAP experiment. There is a prior on Ω_M and 300 low-z SNe. An irreducible systematic is included.





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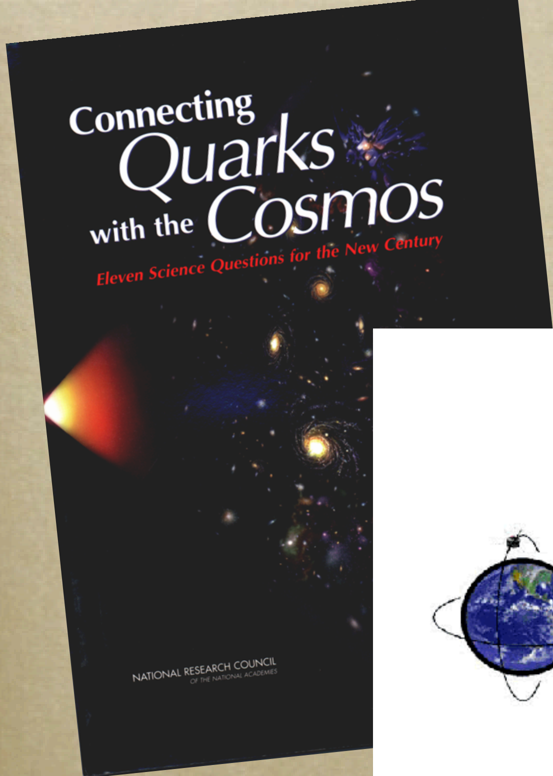

Department of Energy

NASA-DOE
Joint Dark Energy Mission

Paul Hertz / NASA
Robin Staffin / DOE

Endorsed by

Raymond L. Orbach	Edward J. Weiler
Director of the Office of Science	Associate Administrator for Space Science
Department of Energy	NASA
September 24, 2003	September 25, 2003

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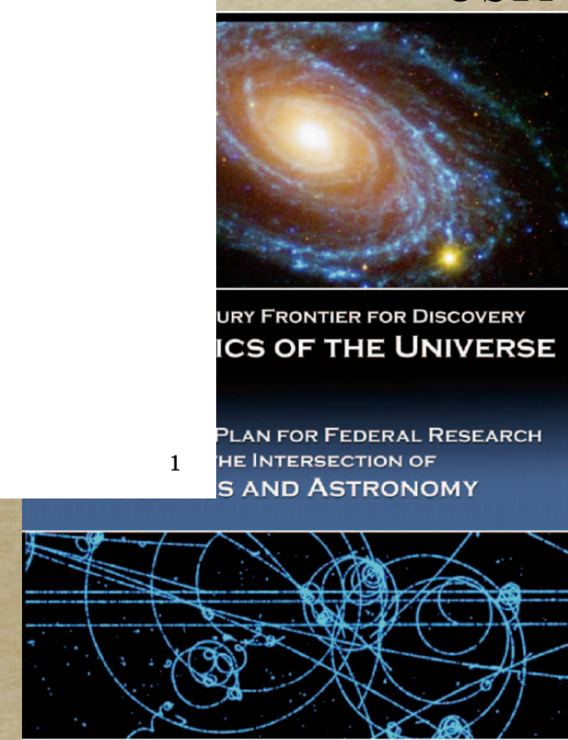
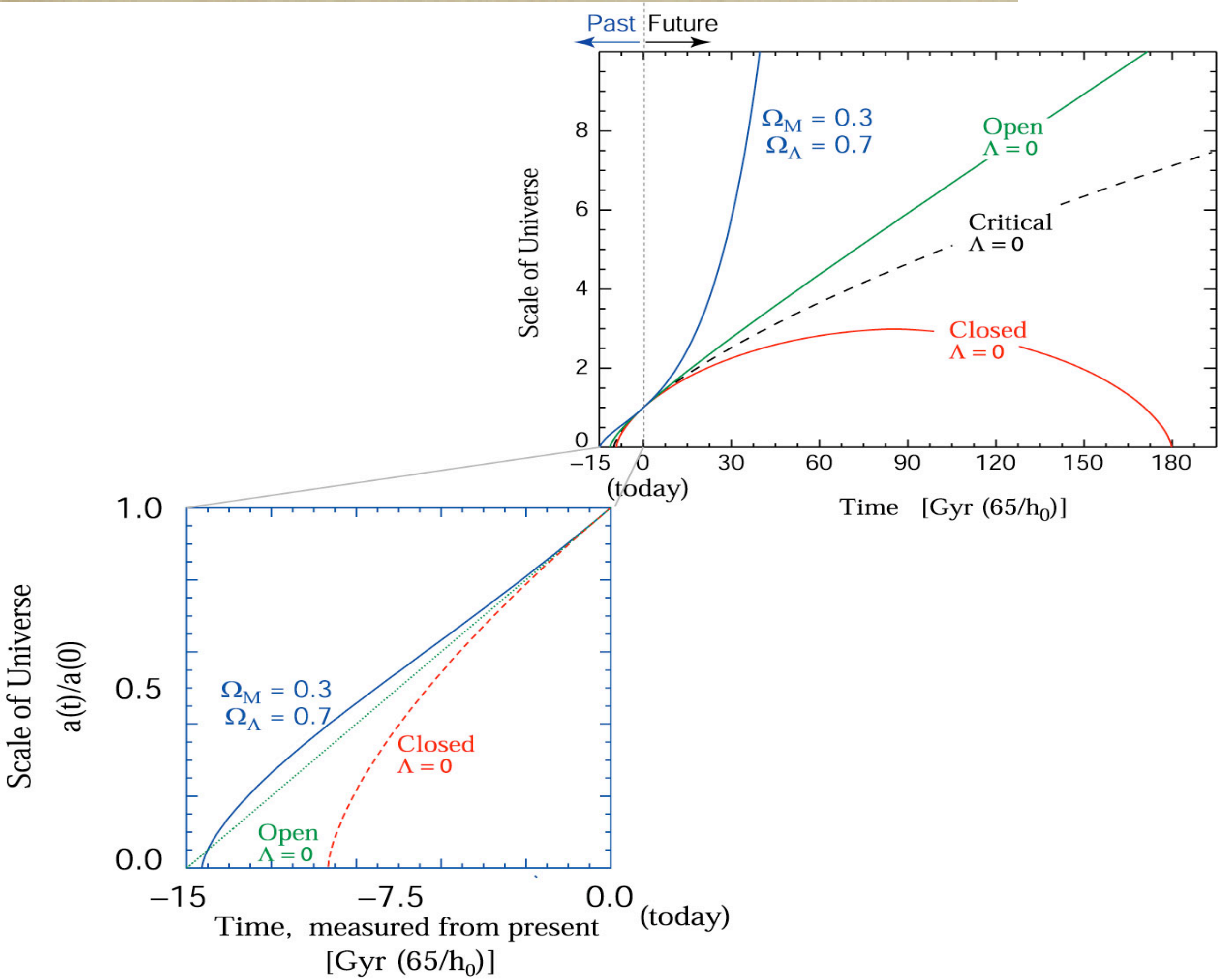
OSTP



Conclusion


Past
Future
Ω_M = 0.3
Ω_Λ = 0.7
Open
$\Lambda = 0$
Critical
$\Lambda = 0$
Closed
$\Lambda = 0$
Scale of Universe
0
2
4
6
8
–15
0
30
60
90
120
150
180
(today)
Time [Gyr (65/h_0)]
1.0
0.5
0.0
Scale of Universe
a(t)/a(0)
Ω_M = 0.3
Ω_Λ = 0.7
Closed
$\Lambda = 0$
Open
$\Lambda = 0$
–15
–7.5
0.0
(today)
Time, measured from present
[Gyr (65/h_0)]